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Essays on the Swedish Electricity Market

by

Bo Andersson

**A Dissertation for the
Doctor's Degree in Economics**

**Department of Economics
Stockholm School of Economics
1997**



**STOCKHOLM SCHOOL
OF ECONOMICS
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Essays on the Swedish Electricity Market

Bo Andersson



**STOCKHOLM SCHOOL
OF ECONOMICS**

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A Summary of the Thesis

The thesis consists of three separate parts. The first consists of four chapters, and this is the major part of the thesis. The four chapters deal with competition and price formation in a deregulated Swedish electricity market. The issues of market power and dominant firms are analyzed from different angles by the use of numerical models of the electricity market. The second part consists of one chapter co-authored with Erik Håden. The main subjects are the electricity prices after a nuclear phaseout and the cost of the phaseout. This is studied in a numerical model, given certain restrictions concerning, for example, emissions of carbon dioxide. The third part consists of two separate chapters. The first is an econometric study of Swedish residential electricity demand using micro data. The second chapter uses a search model to study barriers to energy efficiency in a white-goods market.

Part 1

- Chapter 1.* Introduction to market power and competition in a deregulated Swedish electricity market.
- Chapter 2.* Market structure, profit and the price of electricity: An analysis of different strategies for the firms in the Swedish electricity market.
- Chapter 3.* Competition and market power over time: The case of a deregulated Swedish electricity market.
- Chapter 4.* Market power and competition in a deregulated Nordic electricity market.

Part 2

- Chapter 5.* Power production and the price of electricity: An analysis of a phaseout of Swedish nuclear power.

Part 3

- Chapter 6.* Electricity demand - A study of the Swedish residential sector.
- Chapter 7.* A search cost approach to energy efficiency barriers.

Part 1 A deregulated Swedish electricity market

***Chapter 1.* Introduction to market power and competition in a deregulated Swedish electricity market**

The starting point for the different chapters in part one are recent developments in the Swedish electricity market, with the deregulation of January 1st, 1996, being the principal event. Following the new electricity act, a national electricity market with competition and unrestricted price formation was created. As a consequence, focus in the electricity market has shifted towards questions relating to price formation and competition. In this first chapter the issue concerning the existence of firms that dominate the market, and their potential to influence the market price through strategic behavior, is described. Furthermore, the purpose of this study, which is to develop and apply numerical models to determine what the price level on the Swedish electricity market will be after deregulation, is introduced. The study focuses in particular on the interrelation between concentration on the seller side of the market and price formation. The numerical models are developed so as to permit the implementation of findings from the theory of industrial organization relating to competition in oligopoly markets. In principle the first chapter is a general introduction to the analysis of the deregulated Swedish electricity market with the use of numerical models. The discussion is also a common foundation for the chapters that follow in the first part of the thesis.

***Chapter 2.* Market structure, profit and the price of electricity: An analysis of different strategies for the firms in the Swedish electricity market**

This chapter is concerned with market power and the strategy preferred by power producing firms in the Swedish market. The focus is set on the choice of strategy by firms in the deregulated electricity market, and how this choice affects price formation and profit. Different cases relating to market power and the choice of strategy are analyzed using the numerical model. The first case is set in a perfectly competitive environment, which can be viewed as a reference for what very aggressive competition between firms means for the price level, since the price is equal to marginal cost. The second case is based on Nash-Cournot competition. In the third case the strategy of the dominant firm on the market is to act as a price leader. For the fourth and final case, the dominant firm Vattenfall is assumed to act aggressively on the market, and thus, to compete to preserve or even increase its market share.

From the computed results and from a profit point of view, it is evident that it is the Cournot case that is the dominant strategy in most outcomes. This would therefore be the answer to the question of how the firms would like the market to be formed. However, it may not be this simple, primarily due to the fact that the dominant firm VATT stands to lose substantial market shares if it pursues this strategy and so cuts back accordingly on its output. In the chapter it is discussed whether this may prove to be an inoptimal strategy in the longer run if it turns out that these market shares can only be regained at a high cost to the firm. If this is the case it might be unwise for VATT to cut back on production.

Chapter 3. Competition and market power over time: The case of a deregulated Swedish electricity market

In Chapter 3, the main question concerns the sustainability over time of market power in a deregulated Swedish electricity market. As indicated in the previous chapter the size of the dominant firm in the Swedish electricity market may deter competition after deregulation. It is of great interest whether this is only a temporary issue or whether the dominance is more or less permanent. If the latter is the case, this may be an argument in favor of a split of Vattenfall.

The development of competition and market power over time is explored in the electricity market. The key feature is the incorporation of dynamic oligopoly in a numerical model of the market. For the numerical applications, the main issue is whether a dominant firm can maintain a high mark-up over time. In the analysis, this is explored quantitatively as the relation between the Cournot-equilibrium price and the size distribution of firms in the market.

In the computed modeling results it is shown that it may be possible for a dominant firm to maintain a high mark-up over some time in the Swedish electricity market. However, in the longer run this possibility diminishes as the market grows. In addition, it is also possible for competitors to expand in the market. All in all this reduces the relative power of a dominant firm over time. A word of caution is, however, in place since this process takes at least 10 to 20 years in the model.

Chapter 4. Market power and competition in a deregulated Nordic electricity market

In the previous chapter it was discussed whether a dominant firm may sustain its position in the long run. In Chapter 4, the focus is the recently created joint Swedish and Norwegian electricity market. The object is to analyze whether an expansion of the Swedish market into a Nordic market, taking the restrictions on the transmission lines between Norway and Sweden into account, will dilute the market power experienced by a dominant firm in the Swedish market.

The tool used in the analysis is a numerical model of the deregulated Nordic electricity market, taking the potential bottlenecks in the transmission lines on the border between the two countries explicitly into account. According to the computed results it is clearly the case that the integrated market creates a situation where the competitive environment puts a strong downward pressure on the market price of electricity. During a year with normal levels of precipitation there is, in equilibrium, a large volume of 'contractual flows' of electricity across the border, but only a small amount of physical net flow of electricity. This outcome is a result of so-called reciprocal dumping on the part of the firms whose production is located in either Sweden or Norway.

The analysis in this chapter shows that the integrated and expanded Nordic electricity market is indeed vital for the creation of a well functioning competitive environment for the different actors. It is furthermore clear that the transmission lines and the possible restrictions on these lines play an important role in this. Furthermore, it is concluded that the expansion of the Swedish electricity market into a Nordic market reduces the market power of the dominant firm to such an extent that splitting Vattenfall seems unnecessary.

Part 2 A phaseout of Swedish nuclear power

***Chapter 5.* Power production and the price of electricity: An analysis of a phaseout of Swedish nuclear power**

In this chapter the purpose is to study the effects of different policy scenarios with respect to Swedish energy policy, specifically issues concerning a nuclear phaseout and restrictions on CO₂ emissions. This is done by the means of a dynamic partial equilibrium model of the Swedish energy market where the interdependence between the electricity market and the markets for heating is modeled explicitly. As a basis for the scenarios are the restrictions on future energy policy imposed by the Swedish parliament. It is shown that phasing out nuclear power while restricting future CO₂ emissions to the 1990 level implies a significant increase in electricity prices and a substantial loss in welfare.

Part 3 Residential electricity demand

***Chapter 6.* Electricity demand - A study of the Swedish residential sector**

In this chapter a micro data base, including observations on 4000 individual households' stock of electrical appliances, household size, income, price of electricity paid by the household, and other household specific characteristics, is used in the estimations. Several studies have previously been carried out using aggregate national data to estimate the demand for electricity. Since the underlying theory of consumer demand is based on individual agents behavior this suggests problems with precision of the estimations when aggregate data is used.

The richness of the data base used here suggests that those estimation problems can be avoided, i.e. precise and good estimations of the electricity demand are possible. Two questions are stated beforehand: The first concerns the magnitude of a price effect on electricity demand. The second asks if this detailed information is enough to explain the

variations in individual households' electricity demand, or if additional information (e.g. socio-economic data) is needed on consumers' behavior and habits.

The two conclusions drawn are: First, the hypothesis of a price effect cannot be rejected; and second, that even though detailed household specific data is used, it is only possible to explain a small share of the total variations in electricity demand.

Chapter 7. A search cost approach to energy efficiency barriers

This chapter uses a search-theory approach to show how the existence of a search cost induces a rational consumer to purchase equipment that would not be selected had the consumer been well-informed at the start of the search process and guided by economic efficiency criterion. There is one part of the energy efficiency literature that suggests the existence of significant opportunities to reduce energy use by the implementation of technologies that are cost-effective under today's economic conditions, and yet not fully implemented.

Consumers must base their purchase decisions on observed prices and expectations of equipment performance, and in order to form an accurate base for decision-making the consumer must search for the individual product that meets the specified needs. This search can not be undertaken without a cost. Search costs may therefore explain the incomplete adaptation of seemingly cost-effective equipment. This also suggests a role for interventions in order to facilitate consumers access to information, and thereby reduce the search cost.

It is however shown that under reasonable assumptions the search cost has to be almost eliminated to ensure that consumers choose the most cost-effective, and thereby energy-efficient, model on the market. This implies that the interventions used have to significantly reduce the search cost in order to reduce energy use notably.

Part 1

A deregulated Swedish electricity market

Chapter 1

Introduction to Market Power and Competition in a Deregulated Swedish Electricity Market

1.1 Introduction

The main motivation and starting point for the different essays in this study are recent developments in the Swedish electricity market, with the deregulation of January 1st, 1996, being the principal event. Traditionally, the focus in the electricity market has been on technology oriented issues. Following the new electricity act, a national electricity market with competition and unrestricted price formation was created. As a consequence, the focus in the electricity market has shifted more towards questions relating to price formation and competition. My interest in this area concerns in particular the existence of firms that dominate the market, and their potential to influence the market price through strategic behavior. This interest is motivated especially by the fact that the structure of the Swedish electricity market is characterized by a high degree of concentration among power producing firms.

The purpose of this study is to develop and apply numerical models to determine the price level on the Swedish electricity market after deregulation. The numerical models are used to conduct simulations of price formation in the electricity market. The study focuses in particular on the interrelation between concentration on the seller side of the market and price formation. The numerical models are developed so as to permit the implementation of findings from the theory of industrial organization relating to competition in oligopoly markets. This means that the work in this study is not intended as a contribution to oligopoly theory as such. The intention is rather to contribute to the field of analysis based on numerical models, and in particular to the analysis of electricity market models to which the introduction of individual firms as decision makers is a major contribution.

The tool used in this study is a set of numerical models of the electricity market. In general it can be argued that there are two main purposes in using numerical models. The first is as a way of using numbers in order to illustrate the analytical findings of theory. The second purpose of a numerical model is to use numbers and theory in combination in order to demonstrate some real world issue. The work in this study follows the latter path, which in this case means that numerical models are used to study price formation and competition on the deregulated Swedish electricity market. Thus, although the study is based on theory and formalized modeling, the basic purpose is to elucidate a set of real world issues.

1.2 The Swedish electricity market

1.2.1 Electricity demand and prices

Before going on to a more detailed account of the deregulated electricity market and the model approach, a more general description of the Swedish electricity market would be appropriate. Historically, electricity prices have been decreasing in Sweden. Over the years electricity use increased correspondingly from 4 TWh/year around 1920 to 130 TWh/year in the early 1990s. Although the demand for electricity has continued to increase in recent years, the rate of increase has declined during this period. This is illustrated in Table 1.1, where the consumption of electricity in Sweden is summarized for the years 1970 to 1995.

Table 1.1 Electricity consumption in Sweden for the years 1970 - 1995.

(All figures in TWh/year)	1970	1975	1980	1985	1990	1995
Industry	33.2	38.2	40.1	48.5	53.6	51.7
Residential and commercial	21.4	31.1	42.3	61.7	64.1	72.1
- Of which electric heating	4.7	9.3	14.0	24.8	27.4	28.9
Transportation	2.1	2.0	2.3	2.6	2.5	2.5
Electric boilers	0.7	0.9	1.6	6.6	10.5	7.5
Losses	5.8	7.4	8.2	11.4	9.3	7.5
Total consumption	63.1	79.5	94.4	130.8	139.9	141.5
Import/Export (-)	2.6	5.4	2.8	6.7	-1.8	-1.1

Note: Electric boilers include electricity consumed in power plants and deliveries to gas and waterworks.

Source: NUTEK (1992, 1995 and 1996a).

The per capita consumption of electricity in Sweden is among the highest in the world. In 1994 it was about 14 000 kWh in Sweden, while in countries such as the U.S. and the U.K. the corresponding figures were 11 400 kWh and 5 000 kWh, respectively. The only countries that have a higher consumption than Sweden are Norway, Iceland and Canada. One would expect this to be related to electricity prices, which vary significantly between the countries. In Table 1.2, electricity prices are displayed for a group of countries.

Table 1.2 Electricity prices including taxes in different countries in 1995.

Country	Industry (10 GWh/year)	Residential (3.5 MWh/year)
Australia	37	60
Canada	31	50
Denmark	47	141
France	61	141
Germany	88	199
Japan	111	196
Norway ¹	-	70
Sweden	35	75
U.K.	63	103

Source: NUTEK (1996b).

Note: All prices in öre/kWh.²

¹ Not available for industry, but expected to be among the lower observations.

² 100 öre = 1 SEK = 0.13 US \$, October 3, 1997.

In Table 1.3 the price of electricity in Sweden is summarized, for industrial and residential customers, for the years 1970 to 1995. From this table it can be observed that while the cost of electricity has decreased for the industrial user, it has increased for household users since the early 1980s. This is in spite of the fact that the price net of taxes has decreased for both groups of users. Apparently the tax policy has been to shift taxes towards the residential user and away from industry, resulting in a drop in the industrial price of electricity.

Table 1.3 Electricity prices in Sweden for the years 1970 - 1995.

(All figures in öre/kWh)	1970	1975	1980	1985	1990	1995
Industry (50 GWh/year)						
Net of taxes	27.1	34.8	36.2	30.3	28.8	28.8
Including taxes	28.9	41.1	43.8	38.6	35.0	28.8
Residential (20 MWh/year)						
Net of taxes	43.7	44.9	49.9	44.9	38.7	40.7
Including taxes	46.8	51.2	60.1	56.8	58.7	62.1

Note: All prices are in 1995 SEK.

Source: NUTEK(1995 and 1996a).

From Table 1.3 it is obvious that taxes have become an important share of the prices paid by consumers of electricity. The prices above also include costs for transmission and distribution. The price that is used in the numerical analysis later in this study is the wholesale price of electricity, net of taxes and before losses due to transmission and distribution. The level of this price has varied between approximately 12 and 20 öre/kWh during the late '80s and early '90s, corresponding to a weighted average of approximately 18 öre/kWh (Kraftverksföreningen (1992)).

In order to shed further light on the increase in electricity demand displayed in Table 1.1, it is also important to take into account the development of the relative prices of electricity and oil. As can be seen in Figure 1.1, oil has become more expensive relative to electricity during almost the whole of the period 1970 to 1995. It is not surprising to see that the two other curves show that while the use of oil has dropped dramatically, electricity consumption has increased even more. What has happened is that electricity has been substituted for oil both by industry and the residential sector. This has mainly occurred by conversion from oil to electric heating, a development that was also indicated by the rapid growth in electricity used for heating shown in Table 1.1.

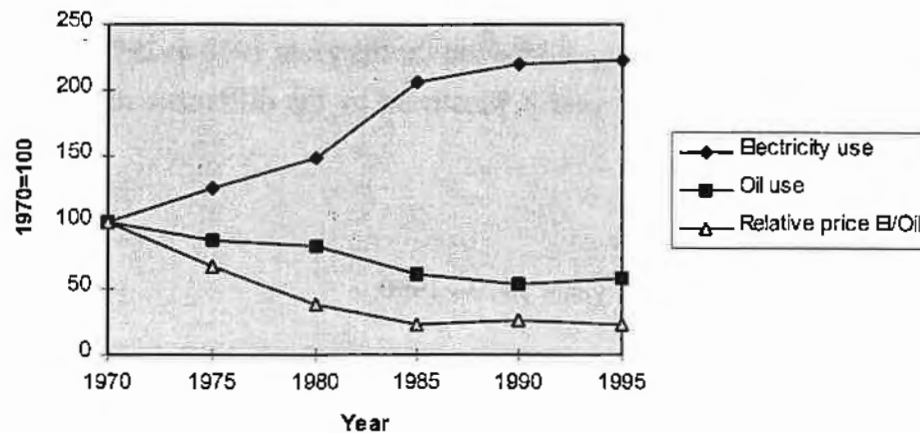


Figure 1.1 Relative prices of electricity and oil together with consumption of electricity and oil in Sweden for the years 1970 - 1995.

All in all, this illustrates the relatively low price of Swedish electricity, which may be a major factor behind the size of domestic electricity-intensive industry and the relatively widespread use of electric heating. These two user groups are the primary components of the high per capita consumption of electricity.

1.2.2 Electricity production and firms

The main explanation of the low electricity prices in the past is connected to the abundant supply of low-cost hydro power. Although the expansion of hydro power slowed down in the 1960s the period of low prices was extended when investments in nuclear power plants started to grow instead. The continuation of low prices can be viewed as a result of continued excess supplies of electricity. This excess supply can, on the one hand, be argued to stem from over-investments in nuclear power, at least at the time. On the other hand, it is also the case that performance measured as output per capacity unit of the nuclear plants has been greater than was expected at the beginning of the nuclear era. As a third alternative, it can be argued that the excess supply was a result of a combination of these factors.

One characteristic of Swedish electricity production in more recent years is the dominance of two main sources of production, namely hydro power and nuclear power. In addition, these two types of power production are of about equal importance in the Swedish electricity system. It should also be pointed out that the annual production capacity from hydro power can vary significantly due to the actual amount of precipitation during the year. Compared to a

normal year it is not uncommon for the supply of hydro power to vary by up to +/- 25 % during a wet year or a dry year. Electricity production for the years 1970 to 1996 is presented in Table 1.4, where the effects of a dry year is illustrated by the difference in hydro power production between 1990 and 1996.

Table 1.4 Electricity production for the years 1970 - 1996.

(All figures in TWh/year)	1970	1975	1980	1985	1990	1995	1996
Hydro power	41.5	57.0	58.1	70.1	71.5	67.0	51.0
Nuclear power	0.06	11.4	25.3	55.8	65.3	66.7	71.4
Other thermal power							
CHP - Combined heat and power	5.8	6.6	9.0	5.6	5.4	8.6	9.9
Condensing power & gas turbines	13.2	3.6	1.0	1.0	0.1	0.9	3.6
Wind power	-	-	-	-	0.01	0.1	0.1
Total	60.6	78.6	93.4	132.5	142.3	143.3	136.0

Source: NUTEK(1995 and 1996a) and Svenska Kraftverksföreningen(1997).

The weather has an influence on the price of electricity, and in power systems with a large share of hydro power, electricity prices are likely to be lower during years with extraordinarily high levels of precipitation than during extremely dry years. The primary interest in this study is, however, the structure of the industry and how this affects competition and price formation. Thus, it is not only the production technologies that are of interest but, even more so, the firms that are in control of the power producing plants. This is a key factor for the analysis of possible impacts on the outcome of deregulation, deriving from to the structure of the Swedish electricity market.

One observation that can be made regarding the structure of the Swedish power industry is that the electricity market is very concentrated on the supply side. If concentration is measured by Herfindahl's index, the result is 0.32, which is roughly equal to having only three producers of equal size on the market.³ The main reason behind this result is obviously the size of the state-owned firm Vattenfall, which has a market share close to 50 %. The major electricity producers and their respective electricity production are presented in Table 1.5.

³ The Herfindahl index is equal to the sum of the squares of the market shares. (Tirole (1988)).

Table 1.5 Electricity production by different producers in 1995.

Firm	Production (TWh)	Share of total (%)
Vattenfall	73.8	51.5
Sydkraft	26.6	18.6
Stockholm Energi	10.5	7.3
Gullspångs Kraft	8.3	5.8
STORA Kraft	5.8	4.1
Gräninge	2.4	1.7
Skellefteå Kraft	2.5	1.7
Skandinaviska Elverk	2.2	1.5
Other firms	11.1	7.8
Total production	143.3	100.0

Source: NUTEK(1996b).

In addition to the domestic electricity market there is the issue of international trade in electric power. Before the deregulation of the Swedish electricity market Sweden was part of an association called Nordel. This association, which still exists, has formed the basis for co-operation among the Nordic countries with respect to electricity production. The main purpose has been to use the connections between the countries' main grids to optimize the production system both over the year and between night and day. The driving force has been the difference in the marginal cost of production between the countries, one country having purely hydro power, one a mixture of hydro and thermal power, and one a national system dominated by thermal power production. The turnover of the power exchange for Sweden, i.e. the sum of exports from and imports to Sweden, was 17.1 TWh in 1995, which is an increase of 4.0 TWh over the year before. The net amount traded is considerably smaller. During 1995 Sweden was a net exporter of 1.7 TWh and in 1994 a net importer of 0.3 TWh. One thing this illustrates is that the Swedish electricity market was not a closed national market before deregulation. It is also clear that the net amount of traded electricity is not a large share of the total turnover of electric power. After deregulation, Sweden and Norway constitute a common marketplace for electricity. The countries make up a free trade area with some restrictions on the transmission of electric power.

1.3 The institutional framework

In the description of the model it will be clear that the national electricity market is viewed as an area without any internal transmission congestions, and thus has been modeled as one national market with one price for electricity. In consequence, there are assumed to be no spatial differences within the national market. It is of course vital to establish that this is a sensible way to represent price formation on the electricity market. The institutional framework of the new electricity market, as described in this section, in combination with the scope of these studies, will be used as a basis in arguing in favor of the chosen approach.

For almost a century, the regulation of the Swedish electricity market was based on the Electricity Act of 1902. One critical area of this legislation was a set of provisions which in effect established the national market for electricity as a number of regional and local monopoly markets. Thus, under these rules the owner of a regional grid or of a local distribution network had an exclusive right to serve all customers connected to the grid or located in the area, but in addition to the exclusive right, there was also an obligation to do this.

However, the formal regulations of the Swedish electricity market were not very detailed. An example of this is the fact that there was no direct regulation of electricity prices or of the rate of returns in the power industry. Instead, control of the industry was exercised through the state ownership of the State Power Board, a power company established in 1909. In 1992 the State Power Board was divided into a new state agency, Svenska Kraftnät, which took over responsibility for the central grid, and a state-owned power production company, Vattenfall. The State Power Board dominated the power industry by a large margin to the second largest firm, and had the role of price leader in the market. In addition to being the largest power producer, the State Power Board was the main supplier of reserve capacity as well as the owner and operator of the central grid, i.e. the 220-400 kV transmission grid.

As of January 1, 1996, a new Electricity Act has replaced the old one from 1902. This change was initiated in 1992 when the State Power Board was divided into Svenska Kraftnät and Vattenfall. Following a process of public investigations and several revisions the new legislation that was implemented includes two key institutional changes designed to achieve competition on the Swedish electricity market. One is to separate the production and supply of electricity from the transmission and distribution service. In practice this means that firms involved in production or sales of electricity are not allowed to engage in the transmission of

electric power, and vice versa. The other is a provision that the transmission grid is open to all agents on the market at prices that are non-discriminating. Thus, all producers, suppliers and traders have equal access to the transmission network.

The transmission and distribution networks are still considered to be natural monopolies and the pricing of this service is regulated by an independent network authority (NUTEK Elmarknad). The supervision of network prices is designed to enhance competition by ensuring that the prices of transmission and network services are fair and non-discriminating. On the central grid, which is owned and operated by Svenska Kraftnät, a so-called point tariff is used which is constructed so as to enhance competition. When a point tariff is used, the distance between a buyer and a seller, transmitting a specific amount of electricity over the central grid, does not affect the transmission price. In addition, the fact that transmission prices do not directly include costs for congestion is positive for the competitive environment. When needed, Svenska Kraftnät enters the market in order to ensure that a contract for a delivery that would congest the transmission system can be completed. In practice this involves buying and selling power in different parts of the system. The cost for this is covered by a fixed fee distributed among all the users of the central grid. The pro-competitive effect of this is that there are never any regionalizations of the electricity market due to bottlenecks in the system.

The short-term balancing of the system, which has the purpose of keeping the frequency and voltage stable in the system, is a responsibility that Svenska Kraftnät is in charge of. This so-called real time dispatch used to be handled by the old State Power Board, or what is now Vattenfall. In the new system Svenska Kraftnät acts by asking producers to increase or decrease their production level, based on the bids that the producers have made to the "regulation market", which is a real short-term market.

For the balance of supply and demand on an hourly basis, the new system makes a dramatic difference. In the old system the so-called merit order dispatch involved a close co-operation between the major power producers on how to utilize available production capacity. The costs of operation for the whole system were minimized by short-term exchanges of power, priced in accordance with a specific formula. This exchange was closed to all small producers, distributors and consumers.

Following the new Electricity Act and new anti-trust legislation in Sweden, the old power exchange, with access limited to major producers only, was closed. In its place a regular spot market for electricity has opened. In concrete terms this means that Swedish producers,

traders, distributors and consumers may fully participate in the existing and operational Norwegian spot market. After the integration of the Norwegian and the Swedish spot markets, the new market has been named Nord Pool. Sellers and buyers now place bids at Nord Pool, thus determining the hour by hour dispatch of available capacity in Sweden and Norway. At Nord Pool the hourly market clearing prices and quantities are determined. There is also a futures market where highly standardized contracts are traded.⁴ Only a small share of total power production (around 15 % in 1996) is traded directly over the spot market. However, the market clearing prices that are formed on the spot market should influence the prices settled on in the bilateral trade of electric power that occurs outside the spot market.

The observation that only a small share of total sales takes place on the spot market points to the fact that a study of price formation in the Swedish electricity market is not equivalent to a study of price formation in Nord Pool. This is also a difference compared to the system in use after deregulation in the U.K and Wales, where all transactions have to be made via the pool. This is also evident in the approaches taken when the electricity market in the U.K. and Wales has been subjected to modeling, by for example Green and Newbery (1992).

To conclude, it can be argued that the new institutional framework described above justifies the approach using a model of the electricity market consisting of one national market with one price for electricity in equilibrium. The question that then arises is which electricity price one should use in the analysis. Or rather, which is closely related to this question, what is the product that is priced?

1.4 The “product”

In the Swedish market, market power is primarily an issue of competition between power producers on the wholesale market. Thus, it is natural to focus on producer prices and use the wholesale electricity price in the analysis. The actual product that is to be priced is more difficult to pin down. The object is to define a product that corresponds to a majority of the contracts between power producing firms and their customers. Most electricity customers have some kind of contract where the maximum power level and energy price are stated. These contracts are usually defined on a yearly basis.

⁴ The future contracts are defined in terms of a given amount of megawatts of electric power for delivery during a future week. Currently it is possible to secure electricity prices up to three years in advance with these contracts.

The ambition is to define a product that adequately represents this situation, and therefore a standardized one-year contract for electric power is used as the product to be priced in the model. This should correspond well to the typical bilateral contracts that are actually in effect today. In addition, it can be pointed out that since the electricity market consists of a mixture of short-run spot market trade and longer-run bilateral contracts, it is reasonable to use a product that is aggregated in time. The one-year contract can be viewed as a weighted average of hourly equilibrium prices.⁵

This product implies an aggregation of the customers as well, since the contract is assumed to cover all customers with a representative time-of-use profile for their electricity use over the year. One possible problem with the one-year contract is that it is not an entirely homogeneous product, since not all consumers have exactly the same load curve over the period of the contract, which is an implicit assumption in this case.⁶

The aggregation in time of the one-year contracts implies that the model is to be defined in energy terms and not in power terms. In order for this to be a good representation of the real world, it is vital to adjust the possible output in energy terms from different technologies and plants according to an approximate measure of the number of hours that they are normally operated. It is for example not likely that plants built as reserve capacity are to be used continuously over an entire year. For hydro power, the energy constraint that is used is based on the precipitation level during a normal year. One problem with hydro power when using a one-year contract as the product is the imposed assumption of spreading precipitation evenly over the year and not considering the spring flood or restrictions in water storage capacity. This is an issue that is not treated explicitly in the present modeling approach.

In conclusion it can be said that the choice of price and product is made in order to fit the purpose of these studies, which is to analyze market power and price formation in the electricity market. The price used and the definition of the model in energy terms imply that it is not a tool intended for optimizing the use of individual plants or production units. There are other models that are designed in detail for this purpose and are better suited to the realization of this important dimension of the production of electric power, which will be discussed further in Section 1.6.

⁵ A vast variety of contracts exist on the electricity market today. The one-year contract used in the analysis does not replicate any of these contracts in detail.

⁶ In the case of for example customers that are electricity distributors with a large share of district heating in their annual sales, this is not a correct assumption for all years.

1.5 Theoretical aspects of price formation

From a theoretical point of view there is no simple obvious solution to how prices on the Swedish electricity market are formed. Crucial to the outcome are the assumptions made concerning the behavior of the firms on the market in combination with how influential they are, i.e. how large their respective market shares are. On the assumption of a perfectly competitive market, all the firms perceive the market price as given. In any oligopolistic market some or all firms are large enough to be able to influence the market price by behaving strategically.

There are numerous ways to model competition in an oligopolistic market. One way of organizing these models is to divide them into two groups: non-cooperative and cooperative. These labels indicate the behavior of the agents or, as in this case, the firms in the market. In non-cooperative models, the firms act on their own to maximize their benefits without any explicit contact with their competitors concerning cooperation. It may however be the case that the firms collude if all firms find this to be beneficial from their own perspective. The issue is then under which circumstances that the collusive behavior is sustainable. The extreme is when the firms cooperate explicitly with the purpose of forming cartels in order to extract monopoly rents from the market.

When modeling the electricity market it is not self-evident whether to use non-cooperative or cooperative models. Historically there are numerous examples of cooperation and consensus in the industry regarding issues ranging from investments in R&D to the optimal utilization of the national electricity system. This cooperation has primarily been channeled through the large industry organization (Kraftverksföreningen) to which almost all power producers belong. Given this tradition of cooperation it may be appropriate to question the expected level of competition after the deregulation. In addition there have recently been a number of transactions resulting in a dramatic increase in the level of cross-ownership between the firms.

However, following deregulation there has been a process whereby firms appear to liberate themselves from the old ties and bonds of cooperation and instead focus on the competitive environment. The cooperation that remains has become much more shallow than it used to be. In addition to this there is the existence of new and stronger anti-trust legislation in Sweden. Thus, the focus in this series of studies is on non-cooperative models, which in effect implies that the firms are assumed to act independently.

It should be pointed out that the resulting equilibria in the models considered here are Nash-equilibria which is the basic solution of non-cooperative games in which each firm behaves in its own self-interest. The concept of a Nash equilibrium is especially appealing since it ensures that a firm can not increase its own profits by choosing an action other than its equilibrium action, given all its competitors actions, and if the vector of actions is in a Nash-equilibrium. This can formally be written:

$$\pi_f(a_f^*, a_{-f}^*) \geq \pi_f(a_f, a_{-f}^*), \quad f=1,2,\dots,F \quad (1)$$

where firm f earns profits π_f and where a_f is the action of firm f and a_{-f} is the action of its competitors, with an equilibrium action denoted by *. When the expression in (1) holds for all f and any feasible action a_f , then a vector of feasible actions is in Nash equilibrium.

For non-cooperative models, another issue is whether the firms on the market make their strategic decision sequentially or simultaneously. If one firm is much larger than the other firm, or group of firms, one possibility is a model where the firms make their decisions sequentially. The large firm is then the leader, moving first, and the small firm observes the leader and then follows with a best response given the move of the leader. This process could be modeled for decisions concerning either quantities to take to the market or the price of the goods sold. If the group of small uninfluential firms are constrained in their production capacity, the large firm may act as a supplier of residual demand. The small firms produce at their capacity and the large firm can adjust its production level in order to maximize profits given the residual demand. The small firms, or competitive fringe, take the price on the market as given (see for example Scherer and Ross (1990), and for a related discussion in connection with the electricity market see Sørgaard (1993)). In these cases the resulting prices are in general above marginal costs (see also Tirole (1988)).

On the electricity market there are several firms large enough to be able to have an influence on the market price. These firms could be assumed to move simultaneously and to compete in price. In general, competition in price, characterized by the Bertrand equilibrium, is considered to involve fierce competition between the firms. In its pure form the Bertrand equilibrium results in prices being equal to marginal costs. If the firms are asymmetric the equilibrium price will equal the marginal cost of the high-cost firm. However, the fact that this outcome depends on each firm on the market having a production capacity available that is large enough to supply the whole market demand on its own, makes this equilibrium very unlikely for the electricity market, where firms are constrained in capacity, at least in the shorter run.

Instead of competing in price, the firms may compete in quantity. If the firms are modeled as having quantity as the decision variable and if furthermore it is assumed that each firm knows the market demand and takes the output of the other firms as given, it is possible to establish a Cournot equilibrium. Thus, here each firm assumes that all the other firms will continue as before after it has made a decision to change its output. The resulting prices under Cournot competition are in general above the marginal costs (see for example Tirole (1988)). The Nash equilibrium with quantities as the decision variable can formally be written:

$$\pi_f(x_f^*, x_{-f}^*) \geq \pi_f(x_f, x_{-f}^*), \quad f=1,2,\dots,F \quad (2)$$

where x_f is the quantity of firm f , x_{-f} is the quantity of its competitors, and with an equilibrium action denoted by $*$.

At a quick glance it appears as if price, and not quantity, is what firms in most markets set. As discussed above this may lead to very aggressive competition between firms, which is something that is not observed in many markets. One possible reason for this is capacity constraints. When firms are constrained in capacity each firm is unable to meet the entire market demand by itself at a low price. In such situations it may be the case that a model where firms are assumed to be competing in quantity will generate a good prediction of the actual equilibrium. Kreps and Scheinkman (1983) have shown that, given certain assumptions, when firms participate in a two-stage game where they first choose quantity (capacity), and then engage in a Bertrand-like competition in price, the outcome is identical to a Cournot equilibrium.

One difference between competition in price and quantity lies in the interaction between the firms in question. In the case of Bertrand-like price competition, prices can be characterized as strategic complements, since the lower the price quoted by the competitor, the lower the price should be that is quoted by the other firm. In quantity competition defined as Cournot competition, the quantities are strategic substitutes, implying that the larger the quantity supplied by the competitor, the smaller the quantity supplied by the other firm should be.

Nevertheless, it may be argued that models based on Cournot or Bertrand competition are not necessarily competing modeling approaches, but rather complement each other (see for example Tirole (1988)). When a market is characterized by a steep marginal cost curve, as could be the case for the electricity market with the existing capacity constraints, a model based on Cournot competition is likely to be a better choice than a model with Bertrand

competition. Cournot competition, where the firms technically set the quantities simultaneously, can be interpreted as capacity competition followed by price decisions. A model based on Bertrand competition may instead be a better alternative for cases where the marginal cost curve is flat instead of very steep.

For this study of the electricity market, the main concern is the level of concentration among the power producers and the related issue of market power. If Bertrand competition is used in the analysis, market power is not going to be a problem. On the other hand, if Cournot competition is assumed in the model, the possible influence on prices of the market power exercised by the dominant firms will be evident in the analysis. Thus, the decision is to use the Nash-Cournot equilibrium as the main assumption for the competitive equilibria in the numerical analysis that follows.

1.6 Modeling the electricity market

After discussing the form of oligopoly competition that may prevail on the electricity market, the next issue is to establish the principles according to which the electricity market should be modeled. It is clear that numerical models are to be used and one aim for the modeling attempt is to incorporate the findings of oligopoly theory in these models. At present there are a large variety of numerical models in general, particularly in the field of energy. In order to structure the discussion of existing energy models and to position the present study with respect to them, an attempt follows to categorize the different groups of models. This will also help to highlight the major contributions of this study to the range of energy models.

One way to group energy models is by separating them in one dimension depending on which agents are active in the model, and in another dimension according to what they are used for or what output the model generates. The first group of energy models, displayed as the bottom row in Figure 1.2, have individual power plants as active agents. This is the most disaggregated group of models in the categorization. Usually the models in this group are very detailed with large amounts of data concerning the production units under study. The primary purpose of these models is to optimize the utilization of individual production units or whole power plants. The time horizon is usually short run with periodicity that can be down to single hours or less. In the second dimension that the models are grouped in, they are separated according to use and output. In the first group of energy models (bottom row) the market is usually viewed as a technology based system and the model as a planning tool used for central decision support. An example of this type of model can be found in IEA-Annex 22 (1994).

Active agents in model	Purpose of model	
	Central decision support	Simulation of market outcome
Groups of coordinated firms		X
Firms		X
Technologies	X	(X)
Power plants	X	

Figure 1.2 Electricity market models: Agents and institutions

In the next group of models, different technologies are considered as individual agents. This means that individual plants using the same technology have been aggregated. One feature of these models is that they allow the mapping of the complete chain of energy conversion from energy resources to useful energy. Thus, fuel switching, development of new technologies, efficiency differences between technologies and technological efficiency improvements over time can be considered, all based on relative prices. In addition, the explicit technologies allow for the disaggregation of energy demand sectors. However, in these models, the final demand for useful energy is exogenous and independent of changes in energy prices. Thus, these energy system models are designed to identify an optimal plan for meeting the exogenous demand, which in turn implies that although there is some market interaction in these models, they are primarily tools for central decision support. Two examples of such energy system models are MARKAL (see for example Fishbone et.al. (1981)) and MESSAGE (see for example Messner (1984)).

Another model that could be mentioned in this group is DELMARK (see Anderson and Håden (1996)). This is a dynamic partial equilibrium model in which six energy markets in Sweden are treated explicitly. These are one national electricity market, three regional markets for district heating, one market for light oil and one for heavy oil. In this model equilibrium

prices and quantities are obtained for each of the markets. In this sense DELMARK is a market model focusing on equilibrium prices and volumes of commercially traded energy, such as electricity, in contrast to the planning perspective of the energy system models.

In the third group of models considered here, it is individual firms that are the active agents, as depicted in row two of Figure 1.2. The introduction of individual firms into numerical energy models is the key feature and chief innovation of the present study. What is new is the introduction of individual firms that actually own the production facilities and thereby control the level of utilization of the individual plants. Technically this means that the individual firms in the model own a portfolio of production units and that the firms then compete with each other on a market for electricity. Thus, if grouped in the other dimension displayed in Figure 1.2, models of this type are not tools for central decision support but rather simulate a market outcome.

The introduction of firms in electricity market models opens the way for strategic interaction among the different agents that are present and active on the market. Thus, it is important for the results for this group of numerical energy models who owns the electricity plants and how the firms use individual production units. In addition, the inclusion of individual firms enables findings from oligopoly theory to be used in numerical models of the electricity market.

Above the level of individual firms there are firms that own shares in each other or for some other reason belong to groups of firms that can coordinate their actions. Thus, in models of this type, the active agents of individual firms have been aggregated into groups of coordinated firms, as indicated by the top row in Figure 1.2. The aggregation of firms in this final group of models follows the observation that a number of both partial and full mergers and acquisitions have recently taken place in the power industry. These deals have been struck both prior to deregulation and subsequent to the integration of the Swedish and the Norwegian electricity markets. In effect this involves Swedish firms buying shares in other Swedish firms and foreign power producers buying stakes in Swedish firms. As indicated in Figure 1.2, this group of models is similar to the models using individual firms in the sense that the output includes simulation of actual market outcomes. The possible influence of coordinated production decisions on the behavior of otherwise independent firms is an additional factor complicating competition on the electricity market. However, the analysis of this group of electricity market models is beyond the scope of this study and remains for future research.

Other recent attempts to model a deregulated electricity market, taking the behavior of individual firms into consideration, have been conducted by Green and Newbery (1992).

Since they analyze the electricity market in the U.K. and Wales, and given the different institutional setup of this market, it is clear that their modeling approach is not one that could be adopted for the Swedish market. This is primarily due to the fact that all transactions on the market in the U.K. and Wales have to go via the pool. The focus of modeling has been on the firms' behavior when placing bids to this power pool. In particular, interest has focused on the bidding process implemented by the different actors in the spot market and how price formation and market efficiency are influenced by this. The analysis includes the establishment of supply schedules for the firms on the market. As already pointed out this approach is not suitable for analysis of the Swedish market, since only a share of the total turnover takes place on the spot market. If only the Swedish spot market were to be studied, the analysis would benefit from the influence of studies related to the electricity market in the U.K. and Wales. For a related discussion see also Klemperer and Meyer (1989).

In conclusion it can be stated that the innovative feature of the electricity market models in this study is the introduction of individual firms and their behavior on the market. This development away from the traditional energy market models is necessary in order to be able to incorporate the findings of oligopoly theory in the analysis. Unless individual firms and their actions are modeled numerically, strategic interactions on the market can not be analyzed in their proper setting.

1.7 Common modeling assumptions

It has now been made clear that the tool used here to study price formation and market power is a numerical model of the electricity market. In Chapter 2 the basic version is introduced, which is then adapted to the different issues under study in the chapters that follow. The basic version of the numerical model is a partial equilibrium model of a deregulated Swedish market for electric power. One partial goal during the development of the model has been to keep it as simple and straightforward as possible, the main reason being that the issues under study and the intuitions resulting from the analysis usually emerge in a clearer and more easily accessible fashion when uncomplicated models are used.

There is of course a trade-off present since simplifications tend to leave out information or circumstances that may be important for the model's ability to capture real world problems. The crucial issue is to simplify when this is possible and does not have a great impact on the outcome. In the outline of the model given below, some critical areas and peculiarities of the

electricity market are pointed out, and also how they have been incorporated. This especially concerns areas where simplifications have been made and discusses how they can be justified.

The analysis focuses on competition between power producers active in the wholesale market. The pricing of the network services and the firms owning the transmission lines are excluded from the model and the market price is modeled as a single price. This is justifiable, since the central grid operator on the Swedish market (Svenska Kraftnät) is involved in buying and selling power in different parts of the system in order to compensate for congestion and to ensure the existence of a single system price. For the transmission lines between Norway and Sweden, the buying and selling of power by the system operator is not used as a means of compensating for congestion. This means that there may be differences in price between the two countries at some times. Thus, in Chapter 4, where competition in a joint Swedish and Norwegian electricity market is studied, the transmission lines between the two countries are modeled explicitly. For a thorough treatment of the pricing of electricity transmission in a perfectly competitive environment, where costs of congestion in the system of transmission lines have been treated explicitly, see also Håden (1997).

As pointed out earlier, the innovative feature of this model is the inclusion of firms acting as individual decision makers in a numerical energy model. The firms in the model are defined as having portfolios of different production units at their disposal. In the analysis, the nine largest electricity producing firms are modeled as active players in the electricity market. The remaining small power producers are aggregated into one group, which is assumed to take the market price of high voltage electric power as given. The firms in the model are simplified “replicas” of the real world firms, both in terms of production capacity and behavior. For example, the largest firm Vattenfall is represented in the model by a replica, VATT, which is a firm in control of the same type and quantity of production units as the real world firm. As is the case with Vattenfall, the firm VATT has a market share of approximately 50 % at the start of the analysis.

The production of electric power is dominated by hydro and nuclear power capacity. As indicated earlier, hydro and nuclear power together account for more than 95 % of power production in Sweden. One additional category of production capacity identified in the model is an aggregate of fossil fueled plants, ranging from units of combined heat and power production that are in operation more than 4,000 hours per year to gas fueled units that are operated only for a few hours per year. The firms in the model and their respective production capacity portfolios are presented in Table 1.5.

Table 1.5 Electricity producing firms and their production capacity.

Firms in the model	Hydro power TWh/year	Nuclear power TWh/year	Fossil power TWh/year	Capacity TWh/year
VATT	35.7	40.4	15.0	91.1
SYD	6.9	17.1	10.6	34.6
STOCK	3.2	4.8	4.0	12.0
GULL	3.9	3.6	1.6	9.1
STOR	3.9	2.1	1.2	7.2
SKAND	1.6	1.2	0.8	3.6
SKELL	2.6	0.4	-	3.0
GRAN	2.4	-	-	2.4
KORS	0.9	0.3	0.3	1.5
Fringe	5.1	-	2.6	7.7

Note: The capacity data are based on the situation in 1991.

Source: NUTEK (1991, 1992 and 1995)

Before the analysis is carried out, a reference scenario, or a base case, is established. The model is calibrated around this base case, which is used to describe the situation on the Swedish electricity market as it was prior to deregulation. The year 1991 is used since this was in principle the last “normal” year before deregulation, both from the point of view of the weather and from the perspective of the start of the industry’s process of preparation for deregulation. The model is calibrated to the 1991 level of electricity production, both in total and for individual firms.

Closely related to production decisions are the costs of production. When using one-year contracts as the product, the analysis will not be entirely accurate if only short-run variable costs are used. In addition to the variable costs, “semi-variable” costs should be included in order to correctly represent the actual production costs that firms face when meeting the demands of the one-year contract. Examples of semi-variable costs are the normal maintenance and upkeep that is necessary to keep the production units running during the period in question. The inclusion of semi-variable costs means a small increase in the costs used, compared with just the short-run variable costs. This does not have a great impact on the results in the model other than lowering the profit levels for the firms somewhat. The production costs for the different technologies, consisting of fuel costs and other short-run operating costs, plus maintenance costs, are displayed in Table 1.6.

Table 1.6 Technologies and variable costs for electricity production.

Technologies	Cost/kWh
Hydro power	1.5 Öre
Nuclear power	7 Öre
Fossil power	9-22 Öre

Source: NUTEK (1991 and 1992), SOU 1995:140 and Nordhaus (1995)

There are two other assumptions regarding the production costs, namely that the costs are constant and firm independent. These assumptions are made since this is consistent with the engineering data that the cost estimates originate from. If more observations were available on realized production costs it may be found that costs are not constant and firm independent. See also Nordhaus (1995) for a discussion on this, especially concerning nuclear power.

One feature of production costs in the Swedish electricity market that should be pointed out is the fact that new power is more costly than power produced in old plants. This is primarily due to the environmental restrictions that are in effect and that rule out the alternatives with the lowest cost. This creates a special situation different from that of most other industries, where technological developments have usually pushed the costs of new production capacity below old production costs.

An issue that is related to the production costs of the firms is the assumption made that all firms are self sufficient in the model. This means that the firms are to produce everything they sell themselves. Instead of this setup one could envision a situation where all firms have closed their one-year contracts and as time goes on the spot market is open for each production hour. A firm which then may have some over-capacity is able to sell some of this on the spot market, where other firms can purchase this and substitute it for their own production. This is profitable for a firm given that the price on the spot market is lower than the own marginal production cost, in which case the firm decreases its production and marginal cost by this transaction. This is then an outcome where firms can buy power from each other while fulfilling their obligations in the one-year contracts. However, to formulate the model in order to allow for this type of trade between the firms is something that is left for a future study.

The demand for electricity in the model consists of the sum of the demand of a large number of relatively small consumers, which is a good representation of the real world group of consumers. Thus, clearly, no market power on the demand side is present in the analysis. This is something that may be an issue in the future, as large and well organized groups of consumers are beginning to take shape in Sweden. However, for the present modeling process it simplifies the work significantly if the consumers are aggregated into one group with a common price elasticity of electricity demand. The elasticities used in the analysis are displayed in Table 1.7. Electricity taxes are not included in the wholesale price in the model. They are instead assumed to be included in the behavior of the demand side.

Table 1.7 Demand elasticities used in the analysis.

Price elasticity	- 0.5
Income elasticity	1.0

For the behavior of the consumers of electric power, it is naturally impossible to correctly generalize demand into one single elasticity. As could be seen in Figure 1.1, there has been both rapid and slow growth in the demand for electricity over the last 25 years. In Figure 1.1 the development of the demand for electricity was discussed with reference to the relative prices of electricity and oil. In the model, there are no alternatives to electricity for the users. Thus, the behavior of the consumers in response to price changes has to come through the own-price elasticity.

The levels of the price elasticity and the income elasticity in Table 1.7 correspond to the findings in a survey of studies of electricity demand elasticities by Bergman and Andersson (1990). The estimated price elasticities were found to be in the range of -0.3 to -1.2 in the long run and between -0.1 and -0.5 in the short run. For the income elasticity, the corresponding range is 0.5 to 1.2 in the long run and 0.2 to 0.8 for the short run estimates. Thus, the elasticities used can be argued to be well in line with the findings in relevant studies.

This concludes the discussion of the modeling approach and the assumptions that are common to the different studies. The remainder of this chapter contains a summary of the three studies where different versions of the numerical model have been used in the analysis.

1.8 Summaries of Chapters 2, 3 and 4

1.8.1 Market power and strategy in a deregulated Swedish electricity market

Chapter 2 is concerned with market power and the strategy that may be preferred by power producing firms in the Swedish market. The focus is set on the choice of strategy adopted by firms on the deregulated electricity market, and how this choice affects price formation and profit. Different cases relating to market power and the choice of strategy by firms are analyzed using the numerical model. The first case is set in a perfectly competitive environment, which can be viewed as a reference for what very aggressive competition between firms means for the price level, since the price is equal to marginal cost. The second case is based on Nash-Cournot competition. In the third case the strategy of the dominant firm on the market is to act as a price leader. For the fourth and final case, the dominant firm Vattenfall is assumed to act aggressively on the market, and thus, to compete to preserve or even increase its market share.

The strategies are also judged according to a sensitivity analysis involving different assumptions regarding the precipitation level. The intention is to show how dry and wet years, and the corresponding shift in the level of hydro capacity that is available to the firms, affect their choice of strategy.

From the computed results and from a profit point of view, it is evident that it is the Cournot case that is the dominant strategy in most outcomes. This would therefore be the answer to the question of how the firms would like the market to be formed. However, it may not be this simple, primarily due to the fact that the dominant firm VATT stands to lose substantial market shares if it pursues this strategy and so cuts back accordingly on its output. This may prove to be an inoptimal strategy in the longer run if it turns out that these market shares can only be regained at a high cost to the firm. If this is the case it might be unwise for VATT to cut back on production.

In conclusion it can be argued that although the Cournot case seems to be the dominant strategy for the firms, a slight hint of caution is called for. The lack of a clear-cut outcome may at times result in cases where the firms opt to pursue different strategies, which in turn may increase the volatility of the market price.

1.8.2 Market power over time

In Chapter 3, the main question concerns the sustainability of market power in a deregulated Swedish electricity market. As indicated in the previous chapter the size of the dominant firm in the Swedish electricity market may deter competition after deregulation. It is of great interest whether this is only a temporary problem or whether the dominance is more or less permanent. If the latter is the case, this may be an argument in favor of splitting Vattenfall.

The development of competition and market power over time is explored in the electricity market. The key feature is the incorporation of dynamic oligopoly in a numerical model of the market. For the numerical applications, the main issue is then whether a dominant firm can maintain a high mark-up over time. Put another way, this can be viewed as a means of checking whether it is necessary to split Vattenfall in order to achieve a high degree of competition in the deregulated market. In the analysis, this is explored quantitatively as the relation between the Cournot-equilibrium price and the size distribution of firms in the market.

As a result, it is shown that it is possible for a dominant firm to maintain a high mark-up over some time in the Swedish electricity market. However, in the longer run this possibility diminishes as the market grows. In addition it is possible for competitors to expand in the market, either in the form of incumbents that are increasing their production potential or of entirely new producers entering the market. All in all this reduces the relative power of a dominant firm over time. A word of caution is, however, in place since this process takes at least 10 to 20 years in the model.

From the results it can be argued that the question as to whether Vattenfall should be split into two separate companies in order to reduce its dominant position in the Swedish electricity market is a complex issue that is not yet fully exhausted. A split would be a major measure and the consequences should be investigated further, especially since from a welfare point of view, there are significant transaction costs involved in a break-up of the firm.

1.8.3 Market power in a deregulated Nordic electricity market

In Chapter 3, where the firms may invest in new capacity it was shown that a dominant firm may not sustain its position in the long run. To a certain extent this result depends on possible barriers to entry. For Chapter 4, the focus is the recently created joint Swedish and Norwegian electricity market. The object is to analyze whether an expansion of the Swedish market into a Nordic market, taking the restrictions on the transmission lines between Norway and Sweden into account, will make a split of Vattenfall unnecessary. For the concept of a single market to be realized, it is of course necessary that the potential for transmission exists between the two previously national electricity markets. In the Nordic case transmission lines already exist, since there has been a history of successful cooperation between the countries to better utilize the national power systems.

The tool used in the analysis is a numerical model of the deregulated Nordic electricity market. The main question asked concerns the extent to which the market power experienced by a dominant firm in one country is affected by the integration of the two markets. This has been analyzed quantitatively as the relation between the Cournot equilibrium price and the size distribution of firms in the two countries, taking the potential bottlenecks in the transmission lines on the border between the two countries explicitly into account.

According to the analysis it is clearly the case that the integrated market creates a situation where the competitive environment puts a strong downward pressure on the market price of electricity. During a year with normal levels of precipitation there is, in equilibrium, a large volume of “contractual flows” of electricity across the border, but only a small amount of physical net flow of electricity. This outcome is a result of so-called reciprocal dumping on the part of the firms whose production is located in either Sweden or Norway.

For years with more extreme levels of precipitation, when available hydro capacity is well above or below the normal level, the result changes somewhat. The physical flows then become large enough to create bottlenecks on the border between Norway and Sweden. As a result, different price regions are established in the two countries.

In conclusion, the analysis has shown that the integrated and expanded Nordic electricity market is indeed vital for the creation of a well functioning competitive environment for the different actors. It is furthermore clear that the transmission lines and the possible restrictions on these lines play an important role in this, particularly during periods with extreme levels of precipitation. Finally, it can be concluded that the expansion of the Swedish electricity market

into a Nordic market has reduced the market power of the dominant firm to such an extent that splitting Vattenfall seems unnecessary.

1.9 Empirical evaluation of the model

From the summaries of the different chapters it is clear that the various versions of the numerical model produce a large set of results. A question that comes into mind after examining all the output, is to what extent the results fit with what can be observed on the real world electricity market after the deregulation has become a reality.

In the period right after the deregulation electricity prices in Sweden increased dramatically. One quick conclusion from this observation is that the large firms immediately realized and took advantage of their dominant positions, as suggested as a possible outcome in Chapter 2. However, the deregulation coincided with a year that was extreme in two ways. First, the year preceding the deregulation was a very dry year, i.e. the levels in the water reservoirs were at a low. Second, the winter of the deregulation turned out to be very cold, which in turn resulted in heating requirements that were greater than usual. All in all this means that the supply of electricity was constrained, i.e. plants with a higher marginal cost have to be run, while in addition the demand for electricity was higher than usual. Thus, the increase in electricity price may have been a natural reaction to the combination of increased demand and decreased possibilities to produce electricity with hydro power, which has a low marginal cost. In order to have a possibility to examine whether the outcome instead could have been a result of firms acting strategically in order to increase the price, observations of the production levels of the individual firms from this time have to be studied.

It is also important to point out that the price that increased dramatically right after the deregulation was the spot market price. The electricity price in the model is, as discussed in an earlier section, the wholesale price of a one-year contract for delivery of electric power. Thus, the easily observed spot market prices are not directly comparable with the output of the model. In order to evaluate the results of the numerical models, a product has to be defined that exists in the real world market and has similar properties as the product that is priced in the model. This should in itself not constitute a problem since the product in the model is defined in order to correspond to a majority of the contracts between power producing firms and their customers. However, price observations on such a contract have to be collected, after which it would be possible to evaluate the results from the numerical models in the proper setting.

1.10 Concluding remarks

In the context of a deregulation it is interesting to note that according to a study by Winston (1993), recent deregulation of several industries in the U.S. has lead to substantial welfare benefits. This consist of both lower prices for the consumers as well as increased profits for the producers. This implies, for example, that a deregulation and the competitive environment that follow may induce more cost-effective operations of firms. This effect may be a significant factor for the outcome of the deregulation of the Swedish electricity market, especially in the longer run, but is however not accounted for in this study.

As a final comment it is hopefully so that this introduction to competition in a deregulated electricity market, has stimulated an interest in the material in its full length.

Chapter 2

Market Structure, Profit and the Price of Electricity: An Analysis of Different Strategies for Firms in the Swedish Electricity Market

2.1 Introduction

The primary goal of the deregulation of the Swedish electricity market is to achieve lower market prices by an increase in competition. Whether this will be the case is still an empirical issue. There is a potential threat to lower prices in that the market structure manifests a very high degree of concentration among electricity producers. In theory, there may be a variety of outcomes to this situation of oligopolistic competition. The question of there actually being an increase in the market price after deregulation, as a result of the concentration in the market, has been investigated by Andersson and Bergman (1995).

In Andersson and Bergman (1995) it was shown that the outcomes under the assumptions of perfect competition and Cournot competition are quite different with respect to the level of the market price. In addition the authors investigated the effects of some pro-competitive measures on the part of the authorities. In this chapter, the analysis from Andersson and Bergman (1995) is extended to some alternative cases and in addition a sensitivity analysis is carried out.

The purpose of this chapter is to study the strategy choices made by firms in the deregulated electricity market and how these choices affect price formation and profit. The main question concerns the strategic outcome the firms would prefer. The analysis is based on a range of cases that differ in terms of market power and the choice of strategy by firms. In particular, the following cases are examined. The first is a perfectly competitive case which can be

viewed as a reference for what very aggressive competition between firms implies for the price level, since the price is equal to marginal cost. The second case is based on Nash-Cournot competition. In the third case the strategy of the dominant firm on the market is to act as price leader. In the fourth and final case, the dominant firm Vattenfall is assumed to act aggressively in the market by competing for market shares.

In addition the different cases are analyzed under different assumptions regarding the precipitation level. The intention is to show how dry and wet years, and the corresponding variations in the level of hydro capacity that is available to the firms, affect their choice of strategy. The tool used to analyze the effects on price formation and profit of the different strategies pursued by the firms in the market, is a numerical model of the wholesale market for electricity in Sweden.

The remaining sections of the chapter are structured as follows. In the next section, the model is presented. This is followed by a description of the base case around which the model is calibrated. After that the four alternative numerical cases are introduced. The results from the different scenarios are presented in the two subsequent sections. This is followed by a section containing the sensitivity analysis, and finally some concluding remarks are made.

2.2 The model

The model will be presented in two main steps. First, the demand for electricity and the production costs of the power-producing firms are described in order to establish an electricity price and the marginal costs for the firms. Second, the competitive environment and different competitive equilibria are discussed. The model is a static partial equilibrium model designed to endogenously determine the market-clearing prices of electricity. The production capacity of each firm is exogenously determined and in that sense it is a short-term model.

2.2.1 Electricity demand

The market demand for electricity consists of the sum of the demands of a large number of relatively small consumers, as discussed in Chapter 1. This implies that there is no market power on the demand side of the market. Following the assumptions that all other product and factor prices are given and that the price elasticity of electricity demand is

constant and equal to η , the demand function is written

$$E = E^0 \left(\frac{P_E}{P_E^0} \right)^{\eta}; \quad (1)$$

where E is total electricity consumption and P_E is the wholesale market price of electricity. The superscript 0 in the variable in question denotes the exogenous value from the period before the deregulation of the market. The formulation of the demand function is based on the calibration approach often used in Computable General Equilibrium models (CGE-models). After the incorporation of an exogenous parameter, in this case the elasticity, the demand function is calibrated using the observed price and quantity from the base year, denoted by superscript 0 in equation (1).

The electricity consumed in the market is mainly produced by the F domestic firms and is to a lesser extent imported. The sum of domestic production and imports equals demand in equilibrium. Since imports are relatively small during a normal year (see Chapter 1) and are not the main issue in this study, they can be omitted in order to simplify the analysis. By denoting production in firm f by X_f , the equilibrium condition for the market is written:

$$E = \sum_{f=1}^F X_f. \quad (2)$$

By substituting equation (2) in (1) an expression for the equilibrium price as a function of domestic production is obtained. This inverse demand function is written

$$P_E = P_E^0 \left(\frac{\sum X_f}{E^0} \right)^{1/\eta}; \quad f=1,2,\dots,F. \quad (3)$$

The price in the model, P_E , is the wholesale electricity price. It is assumed that the electricity price is the market clearing price of one-year contracts for delivery of electric power to customers with a representative time-of-use profile for their electricity use over the year.⁷

⁷ The electricity price that faces the end-user usually consists of four different components, not counting taxes. Each component is intended to represent a specific cost. Thus, there is one completely fixed fee, supposed to cover the distributors' costs for metering, administration etc., a second part represents the transmission costs on the national and regional grids and is dependent on the highest transmitted power level, a third part reflects the customers power use during peak-load periods and finally, the last part which is the energy fee representing the cost for the electric energy used by the customer. The electricity price in the model represents the last of the four

2.2.2 Production costs

The firms in the model act independently of each other and seek to maximize their profits. A firm is defined as a "portfolio" of production units and two main categories of production capacity are distinguished. The first category consists of nuclear and hydro power capacity. This is the dominant production category since, as was shown in Chapter 1, hydro and nuclear power together account for more than 95 % of power production in Sweden. The second category of production capacity is an aggregate of fossil-fueled plants, ranging from units of combined heat and power production that are in operation for more than 4,000 hours per year, to gas-fueled units that are operated for only a few hours per year.

In the analysis the nine largest electricity producing firms are modeled as active players in the electricity market. The remaining small power producers are aggregated into one group, which is assumed to take the wholesale market price of electric power as given. The firms in the model were discussed in Chapter 1. For the reader's benefits, the firms that are present in the model and their respective portfolios of production units are displayed in Table 2.1.

Table 2.1 Electricity producing firms and their production capacity.

Firms in the model	Hydro power TWh/year	Nuclear power TWh/year	Fossil power TWh/year	Capacity TWh/year
VATT	35.7	40.4	15.0	91.1
SYD	6.9	17.1	10.6	34.6
STOCK	3.2	4.8	4.0	12.0
GULL	3.9	3.6	1.6	9.1
STOR	3.9	2.1	1.2	7.2
SKAND	1.6	1.2	0.8	3.6
SKELL	2.6	0.4	-	3.0
GRAN	2.4	-	-	2.4
KORS	0.9	0.3	0.3	1.5
Fringe	5.1	-	2.6	7.7
Total	66.2	69.9	36.1	172.2

Note: The capacity data are based on the situation in 1991.

Source: NUTEK (1991, 1992 and 1995)

components and is thus net of distribution costs and taxes. This component is the one that is influenced by the level of competition among the producers.

The important idea in defining a firm as a portfolio of production units is that it is individual firms, instead of technologies, that compete with each other in a market for a tradable energy such as electricity. Furthermore, in this context it is important who owns the plants and how the owner uses the production units.⁸

The first production category, which consists of nuclear and hydro power capacity, is denoted in the model by i , where $i=1,2$ to represent hydro and nuclear, respectively. The second category of production capacity, which is an aggregate of fossil-fueled plants, is denoted by j . The output from plants in category i in firm f is denoted X_{fi} while output in the second category of plants is denoted X_{fj} . The total output for firm f , denoted by X_f , is then given by

$$X_f = \sum_{i=1}^2 X_{fi} + X_{fj}; \quad f=1,2,\dots,F. \quad (4)$$

The next step is to define the cost of production for the firm. For units in category i this is defined by

$$C_{fi} = c_i X_{fi}; \quad X_{fi} \leq K_{fi}; \quad i=1,2.; f=1,2,\dots,F, \quad (5)$$

where c_i is a unit cost of operation that is firm-independent, as discussed in Chapter 1. Output from units in category i is limited to available capacity K_{fi} .

The cost function for units in category j is then written

$$C_{fj} = a_j X_{fj} + b_j \left(\frac{X_{fj}}{K_{fj}} \right)^\phi X_{fj}; \quad f=1,2,\dots,F, \quad (6)$$

where a_j denotes the fuel and other operating costs per unit of output in the least expensive type of combined heat and power production units. The sum of $a_j + b_j$ is the corresponding cost in oil-fired condensing power plants. In order to approximate the significantly higher production cost of gas turbines, which have to be made use of at times when all other

⁸ One ownership issue related to production capacity concerns the fact that not all individual firms that have some nuclear power in their portfolio own this independently, instead, they may own a nuclear plant jointly with several other firms. This raises the question of the extent to which it is possible to regard a firm's decision as to how to run its nuclear capacity as a truly independent choice. It is, however, the case that the larger firms, Vattenfall and Sydkraft, do have their own nuclear power plants, and since it is shown in the analysis that follows that it is the production decisions taken by the large firms that have the greatest impact on the results, this ownership issue should not constitute a problem.

production capacity at the firm's disposal is already fully utilized, the exponential parameter ϕ is introduced as a positive number greater than unity. Thus, when production is small and the values of X_{fj} are low the marginal cost is close to a_j . When production and the value of X_{fj} are equal to the capacity K_{fj} the marginal cost is equal to $a_j + b_j$, and then increases rapidly as X_{fj} grows.

Each individual firm then allocates output between the different production units in the portfolio in order to minimize its costs for each given level of output. The firm's cost for producing X_f can be regarded as the solution to the minimization problem.

$$\begin{aligned}
 C_f(X_f, K_{f1}, K_{f2}, K_{fj}) &= \min_{X_{f1}, X_{f2}} \sum_{i=1}^2 C_{fi} + C_{ff} \\
 \text{s.t. } \sum_{i=1}^2 X_{fi} + X_{ff} &\geq X_f && ; \mu_f \\
 -X_{fi} &\geq -K_{fi} && ; \lambda_{fi}; i=1,2 \\
 X_{fi}, X_{ff} &\geq 0 && ; i=1,2
 \end{aligned} \tag{7}$$

The Lagrange function is then written

$$\begin{aligned}
 L = \sum_i c_i X_{fi} + a_j X_{ff} + b_j \left(\frac{X_{ff}}{K_{ff}} \right)^\phi X_{ff} \\
 + \mu_f \left(X_f - \sum_i X_{fi} - X_{ff} \right) + \lambda_{fi} (X_{fi} - K_{fi});
 \end{aligned} \tag{8}$$

i=1,2; f=1,2,...,F,

with C_{fi} and C_{ff} defined from equations (5) and (6), respectively. The first-order Kuhn-Tucker conditions then yield

$$\left. \begin{aligned} c_i - \mu_f + \lambda_{fi} &\geq 0 \\ X_{fi} (c_i - \mu_f + \lambda_{fi}) &= 0 \end{aligned} \right\} \tag{9}$$

i=1,2.

and

$$\left. \begin{aligned} a_j + b_j \left(\frac{X_{ff}}{K_{ff}} \right)^\phi - \mu_f &\geq 0 \\ X_{ff} \left(a_j + b_j \left(\frac{X_{ff}}{K_{ff}} \right)^\phi - \mu_f \right) &= 0 \end{aligned} \right\} \tag{10}$$

The Lagrange multiplier μ_f can be interpreted as the firm's marginal cost, thus $\mu_f = \partial C_f / \partial X_f$. The other multiplier, denoted by λ_{fi} , which is associated with the capacity constraint, can be interpreted as a firm-specific scarcity rent on firm f 's production capacity in category i . The first-order Kuhn-Tucker conditions above ensure that the firms utilize their production capacity in merit order and only run a specific technology when it is cost-effective. The firm's marginal cost, μ_f , which is derived from the cost minimization problem, can also be displayed as in Figure 2.1.

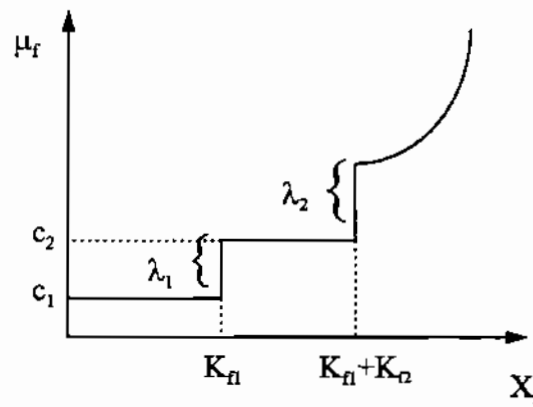


Figure 2.1 Marginal cost function for firm f .

It can be concluded from Figure 2.1 that the cost function is non-differentiable for $X_f = K_{f1}$ and for $X_f = K_{f1} + K_{f2}$. This reservation should be kept in mind when interpreting equation (11) below where $\partial C_f / \partial X_f$ is present.

In conclusion, all this implies that total and marginal costs for the firms are determined by the cost functions for the different production categories and the portfolio of production units controlled by each separate firm.

2.2.3 Competitive equilibria

Total production, and thus the price level, is determined in the model by profit maximization behavior on the part of the producers and by the competitive environment the firms act in. From the discussion in Chapter 1 it is clear that several possibilities concerning the

competitive environment exist and that there is no simple or obvious theoretical solution to how prices may be formed in the electricity market.

Given recent developments in the electricity market, the focus is on non-cooperative models. One major concern in this study is the level of concentration among power producers and the related issue of market power. By assuming Cournot competition in the model, the possible influence on prices of the market power exercised by the dominant firms will be evident in the analysis, as argued for in Chapter 1. Thus, the decision is to use the Nash-Cournot equilibrium as a major assumption for the competitive equilibria in the numerical analysis.

It would nevertheless be interesting to allow for other forms of strategic behavior as an informal test of different outcomes. This would also permit a comparison between different strategy approaches on the part of the firms in the market. Thus, in order to allow for several different cases the model is closed by a conjectural-variation condition, i.e.

$$P_E + X_f \frac{\partial P_E}{\partial X} \left(1 + \frac{\partial X_{-f}}{\partial X_f} \right) = \frac{\partial C_f}{\partial X_f}; \quad f=1,2,\dots,F. \quad (11)$$

where X denotes total output of all firms, and the term X_{-f} denotes total output of all firms except f .⁹ This allows us to adapt the model to different assumptions of how competition in the electricity market is formed.

This completes the description of the model and various conceivable competitive equilibria. The model is empirically implemented using production cost and capacity distribution data from the Swedish power industry, and calibrated to the actual situation in 1991. The model is solved by means of GAMS (see Brooke et.al. (1988)), and a solution is obtained in less than 25 seconds on a Pentium PC.

2.3 The base case

Before the analysis is carried out a reference scenario, or a base case, is established. The model is calibrated around this base case, which is used in order to describe the situation in the Swedish electricity market as it was prior to deregulation. This implies that VATT is

⁹ Firm f 's conjectural variation is the rate $\partial X_{-f} / \partial X_f$ at which the firm conjectures that the output of other firms would change if f 's own output changed.

assumed to act as price leader in the market and to apply marginal cost pricing subject to a rate of return constraint. This means in turn that the base case equilibrium price corresponds to VATT's marginal cost of production plus a mark-up based on the required rate of return. The model is calibrated to the 1991 level of electricity production, both in total and for individual firms, and to the wholesale market price of electricity.¹⁰ The year 1991 has been chosen as the base year since it can be viewed as the last normal year prior to deregulation, both from a meteorological perspective and from the point of view that the firms in the market had not yet started to act strategically in anticipation of the reform.

Table 2.2 Technologies and variable costs of electricity production.

Technologies	Cost/kWh
Hydro power	1.5 Öre ¹¹
Nuclear power	7 Öre
Fossil power	9-22 Öre

Source: NUTEK(1991 and 1992), SOU 1995:140 and Nordhaus (1995)

Estimates of the variable costs associated with the different sources of power generation used in the model were discussed in Chapter 1 and are displayed in Table 2.2 for the reader's benefit. When using one-year contracts as the product, the analysis will not be entirely accurate if only the short-run variable costs are used, as argued in Chapter 1. In addition to the variable costs, such as fuel costs and other short-run operating costs, "semi-variable" costs should be included in order to correctly represent the actual production costs that the firms face during the one-year contract.

2.4 Four alternative cases

In order to establish which strategy would be preferred by the competitors in the market, different cases with different strategies are examined. Naturally this will not be an exhaustive list of all the possible combinations of strategies that can be pursued by the firms, but the

¹⁰ The price formation in the model is based on one-year contracts for customers with a representative time-of-use profile for their electricity use over the year.

¹¹ 100 öre = 1 SEK = 0.13 US \$, October 3, 1997.

intention is to cover some of the more interesting alternatives. The discussion around the different strategies is based on the Conjectural Variation equation introduced as equation (11) above. As is clear from this equation the setting with a conjectural variation term opens the way for different assumptions about the strategies pursued by the firms competing on the market. It should be pointed out that not all of these cases constitute Nash-equilibria. The idea is to introduce different feasible sets of strategies in order to illustrate the impact on prices and profits of the different actions taken by the firms.

The first case is based on marginal cost pricing and is in a sense a "floor" indicating how far down fierce competition can possibly push the market-clearing price in the electricity market. In terms of equation (11) this can be viewed as a case where each firm f believes that an increase in its output is matched by a decrease in the other firms' output, thus leaving total industry output unchanged. The conjectural variation term is then equal to -1 for all firms, as displayed in Table 3, and equation (11) can be written as the standard perfectly competitive market price-equal-to-marginal-cost condition. Capacity is assumed to be given and the price is then determined as the marginal cost or as the price that clears the market given the existing capacities. In the numerical examples that follow this case will be referred to as the perfectly competitive case.

Table 2.3 Value of conjectural variation term for different competitive equilibria.

Firms in the model	Perfectly competitive case	Cournot case	Price leader case	Market share case
VATT	-1	0	0	-1
SYD	-1	0	-1	0
STOCK	-1	0	-1	0
GULL	-1	0	-1	0
STOR	-1	0	-1	0
SKAND	-1	0	-1	0
SKELL	-1	0	-1	0
GRAN	-1	0	-1	0
KORS	-1	0	-1	0
Fringe	-1	-1	-1	-1

The second case that is estimated is based on Cournot competition. In a Cournot equilibrium it is assumed that each firm knows the market demand and takes the output of the other firms as given. This implies that each firm only considers the effect on the market price of its own

output. In terms of equation (11) above this corresponds to a conjectural variation set equal to 0, as displayed in Table 2.3. As can be seen in Table 2.3 the firms collected in the fringe do not behave like this. Since this group consists of a large number of small firms that each have no impact on the market price it is assumed that the fringe firms behave as price takers on the market. Thus, the conjectural variation term is equal to -1 for the fringe, implying that the firms in this group produce at the level where price equals marginal cost. In the numerical analysis that follows this case will be referred to as the Cournot case.

The third case to be estimated is termed a price leader case. This case is influenced by the Stackelberg leader-follower concept (see for example Tirole (1988)). Since only one stage exists in the static model used here the concept has to be adapted to fit the circumstances. A dominant firm can be assumed to act as a price leader supplying the residual market demand. The dominant firm may thus achieve a higher market price than would have been possible if instead it had produced at full capacity, while the other smaller firms had produced at their capacity. In the electricity market there is one firm that can naturally to be modeled as a leader, namely Vattenfall. In this setting of the model then, the firm VATT assumes the role of price leader and will use its dominant position on the market to influence the price, while the other firms produce at their capacities. This implies that price equals marginal cost for the smaller firms, which in turn means a conjectural variation equal to -1 in terms of equation (11). VATT is assumed to take the production of the other firms as given and will consider its own production to be the sole influence on the market price. Thus, for the dominant firm the conjectural variation term is set at 0, as displayed in Table 2.3. The description of a market where a dominant firm competes with several smaller firms fits well with the actual structure of the Swedish electricity market. This case is termed the price leader case in the following sections of numerical exercises.

In the fourth and last case, the dominant firm VATT is assumed to act so as to preserve, or even expand, its market share. This derives from the fact that, as will be clear from the results of the two previous cases, it is VATT that has to reduce production significantly in order to maintain a large mark-up. Given that market shares may be hard to regain once they are lost and that future profits may depend on access to the market, VATT may possibly follow a strategy of aggressive pricing in order to maintain its market share. In terms of equation (11) this implies a conjectural variation term equal to -1 for VATT, which then supplies the market until the price equals its marginal cost. However, for all its competitors the conjectural variation term is assumed to equal 0, except for the competitive fringe, where it equals -1 as usual. The conjectural variation term of 0 for the other firms implies that they are assumed to

consider only changes in their own output when evaluating effects on the market price. The term for this case in the numerical applications will be the market share case.

No uncertainty exists in the model. However, in the electricity market, both the supply of and the demand for electricity is uncertain. The primary source of uncertainty is the weather, since the supply of hydro power depends on actual precipitation and the demand for electricity in Sweden will be higher than usual during an extremely cold winter. The deterministic outcome of the model can be viewed as the solution in expectancy terms of a case where the probabilities of different precipitation levels have been used. In order to take different weather conditions into account, the model will be solved deterministically for three different levels of precipitation: a normal year, a wet year and a dry year. This sensitivity analysis enables us to study both how the level and how the spread of the results in the different cases are affected by the prevailing weather conditions.

2.5 Electricity prices, firm profits, quantities and market shares

This section consists of two main parts. In the first, price formation in a deregulated electricity market is studied. This sheds light on how the price of electricity may develop differently depending on the structure of the market and the competitive behavior of the power producers that are active in the deregulated market. The second part is concerned with what the profits and market shares will be for the individual power producers in a deregulated electricity market, given the market structure and competition.

2.5.1 Price formation in a deregulated electricity market

The production level and the price of electricity that the base case has been calibrated to are a natural norm for comparison when the effects of deregulating the electricity market are analyzed. If the competitive environment in a deregulated Swedish wholesale electricity market were fierce enough to force the price to equal the marginal cost, it is obvious from Table 2.4 that the price of this perfectly competitive case would be lower than the base case price. The fact that the perfectly competitive equilibrium price is 84 % of the base case price indicates that the potential for lowering the market price by increasing competition is quite large. From the perspective of the state authorities, one of the main reasons for the whole process of deregulating the electricity market has been to make some progress towards this end.

It is then interesting to observe what the outcomes are in the alternative cases. It is clear that the results will be different, but the main concern is the magnitude of the difference. In the second case the model is solved for the Cournot case with the given firm structure. In this case the new price level is significantly higher, and electricity production is substantially lower, than the perfectly competitive case, or even the base case levels. This result is also more pronounced than in the case where the dominant firm VATT is assumed to act as price leader in the wholesale electricity market, as can be seen in Table 2.4.

Table 2.4 Computed production and equilibrium prices in the electricity market.

	Equilibrium price Öre/kWh	Equilibrium price in % of Base case	Production TWh
Base case	18.0	100	142.5
Perfectly competitive case	15.1	84	155.7
Cournot case	24.5	136	121.4
Price leader case	20.8	116	132.0
Market share case	17.5	97	144.6

Note: All figures are before losses and prices are excluding V.A.T. and electricity tax per kWh.

A further analysis of the results show that in the price leader case, as well as in the Cournot case, it is principally the largest firm, VATT, that acts to raise the price level by holding back production. In the Cournot case, where this is most accentuated, VATT reduces nuclear production from 40 TWh/year in the perfectly competitive case to only 14 TWh/year. In terms of total production by VATT this corresponds to a reduction from 76 TWh/year to 50 TWh/year. These results differ quite markedly from the case where VATT is assumed to compete for a large market share instead. The outcome in this case, as displayed in Table 2.4, suggests a price level which is far below the Cournot level, even though all larger firms except VATT are assumed to behave as in the Cournot case. In fact, the price level in the market share case even drops somewhat below the base case level. Primarily this is due to an increase instead of a decrease in output from VATT.

From Table 2.4 it is clear, as one would expect, that the cases yield different results. The interesting aspect is how different the results are from each other, i.e. the magnitude of the difference in price level between the cases. Obviously the Cournot case would imply electricity prices that are much higher than for any of the other outcomes. This applies even to

the case predating the deregulation. The spread in the results indicates that it is not at all clear what the actual price level is that can be expected. In order to get a clearer idea of the different strategies' importance for the firms and which strategy is preferred, it would be helpful to have some indication of the profit levels in the different cases. Thus, the issue of the firms' profit is the main question in the next section.

2.5.2 Profit levels and market shares from different strategies

For the choice of strategy for the individual firm, the most important aspect of a deregulated electricity market is not necessarily price formation. It is nevertheless important since it is closely related to what matters most, namely, profits. The operating surplus will be calculated for the firms in the electricity market in order to analyze how different strategies affect earnings. With knowledge about the profit levels, it may be obvious which strategies are preferred by the agents in the electricity market. Thus, we shall analyze whether there is one single strategy that actually generates the highest profits for the firms in the market. The measure used for the firms' financial situation is defined as revenue minus variable cost. In the perfectly competitive case, the operating profit is normalized to 100. The computed profit, output quantities and market shares for the firms are displayed in Table 2.5.

Table 2.5 Computed profit, quantity and market share levels in the perfectly competitive case.

Firms in the model	Profit	Quantity (TWh)	Market share (%)
VATT	100	82.7	53.1
SYD	100	28.0	18.0
STOCK	100	10.5	6.7
GULL	100	8.6	5.5
STOR	100	7.2	4.6
SKAND	100	3.6	2.3
SKELL	100	3.1	2.0
GRAN	100	2.5	1.6
KORS	100	1.5	1.0
Fringe	100	7.9	5.1

In the first alternative case, the Cournot case, it was clear in the previous section that the price level was dramatically higher than in the perfectly competitive case, the primary reason being a much lower level of output in the industry. As can be seen in Table 2.6, this higher price level leads to increased profits for the firms. It is striking that although it is the dominant firm that has the greatest influence on the price, by making a large reduction in its output, it is the smaller firms that benefit most from the increase in mark-up. Of course this is due to the fact that the smaller producers maintain a relatively high production level. In the Cournot case, all smaller firms experience nearly a doubling of profits while increasing their market shares compared with the perfectly competitive case. Obviously this strategy appears to have advantages for the smaller firms. The dominant firm VATT, which reduces output dramatically, experiences a corresponding drop in its market share to only slightly above 40 % from a level clearly above 50 %, which was the outcome in the perfectly competitive case as well as in the base case.

It should be pointed out that the results from the Cournot case reflect the profit level for the dominant firm VATT when it cuts back on production supplied to the market by closing some plants. It is possible that instead of not producing the power, VATT may sell the corresponding volume in a different market, where its supply does not affect the price on the Swedish electricity market. One alternative may be to export the power to customers outside the Swedish electricity market. In that case VATT's profits would increase, and from this it follows that VATT's profit in Table 6 can be viewed as a lower bound to its earnings potential as a Cournot player.

As a small exercise to illustrate this point it may be assumed that VATT could actually sell power somewhere else instead of closing plants. If this could be done at a price equal to 75 % of the market price in Sweden, VATT's profit level would increase from 123 in the Cournot case to 168. Thus, if VATT manages to sell the power and still maintain its mark-up on the Swedish market, its profit level could be well in line with the competitors in the Cournot case.¹²

¹² After all one-year contracts are closed and the spot market is open, VATT could sell some of the power otherwise held back in the Cournot case to firms producing at their capacity. This could allow the other firms to reduce their most expensive output and substitute it with power bought from VATT.

Table 2.6 Computed profit, quantity and market share levels in the Cournot case.

Firms in the model	Profit	Quantity (TWh)	Market share (%)
VATT	123	50.3	41.4
SYD	185	24.4	20.0
STOCK	199	11.3	9.3
GULL	190	9.3	7.7
STOR	183	7.4	6.1
SKAND	190	3.8	3.1
SKELL	169	3.1	2.6
GRAN	169	2.5	2.1
KORS	189	1.6	1.3
Fringe	174	7.7	6.3

It is noteworthy that the further away from the perfectly competitive case that the outcome of the strategies used by the firms is, the more profits generally increase. Thus, when VATT acts as price leader, the profits are higher than in the perfectly competitive equilibrium, although not as high as in the Cournot case. The computed profit, output quantities and market shares for the firms in the case where VATT assumes the role of price leader are displayed in Table 2.7.

As can be seen in Table 2.7, the market share for VATT also remains much lower in this case, where VATT is the price leader. Compared with the Cournot outcome, it can be noted that SYD no longer holds back some of its production and in consequence its market share is up substantially compared with the previous cases.

Table 2.7 Computed profit, quantity and market share levels in the price leader case.

Firms in the model	Profit	Quantity (TWh)	Market share (%)
VATT	106	52.2	40.0
SYD	171	33.4	25.3
STOCK	162	11.4	8.6
GULL	155	9.3	7.1
STOR	151	7.4	5.6
SKAND	156	3.8	2.9
SKELL	143	3.1	2.4
GRAN	140	2.5	1.9
KORS	156	1.5	1.1
Fringe	143	7.4	5.6

In the last case, where VATT is assumed to compete for market shares, VATT also maintains a high output level. The corresponding profit levels, output quantities and market shares for the firms are displayed in Table 2.8. As expected, the strategy pursued by VATT results in a much higher market share than in the two previous cases, where VATT held back its output. Furthermore, it is noteworthy that the profits generated are almost as high for VATT in this case as in the Cournot case. This indicates that although the price is lower, the increased volume almost offsets this from a profit perspective. However, the other firms clearly prefer cases where VATT does not compete for market shares.

Table 2.8 Computed profit, quantity and market share levels in the market share case.

Firms in the model	Profit	Quantity (TWh)	Market share (%)
VATT	120	76.1	52.6
SYD	121	24.1	16.7
STOCK	124	10.5	7.3
GULL	121	8.8	6.1
STOR	121	7.3	5.1
SKAND	122	3.7	2.6
SKELL	117	3.1	2.1
GRAN	117	2.5	1.7
KORS	122	1.5	1.0
Fringe	113	7.1	4.9

As for the observed behavior of the real world firms after deregulation, there seems to be no direct indication that Vattenfall is involved in significant cut-backs in production. The analysis in the model has so far been for a normal year. For this typical single year, the results indicate that it is not self-evident that all firms would prefer the Cournot outcome. Clearly the world is not made up of just one single normal year. One interesting factor concerns time and the repeated game and in Chapter 3, the issue of market power over time is the main subject of investigation. Another factor that may be of great importance for the strategic choices are the fluctuations in hydro supply, i.e. the existence of wet and dry years. The main reason this is important are the differences in the distribution of hydro capacity between the portfolios of the firms, which in turn mean that the firms are not affected in the same way by changes in the precipitation level. The issue of varying precipitation levels and hydro capacity is the main concern of the next section.

2.6 Sensitivity analysis: Supply of hydro power

Varying precipitation leads to differing production potential for the firms with hydro capacity in their portfolio of production units. At a given level of output this variation means an increase or a decrease in the firm's marginal costs in a dry year or a wet year, respectively. Since hydro capacity is not uniformly distributed among the firms, these variations will have a differing impact both on the marginal costs of different firms and on their relative size in the market. These factors may influence the preferred strategy choice of the firms. Variations in the precipitation level can thus be said to have an effect on the competitive environment.¹³

The supply of hydro power can vary by up to $\pm 25\%$ between wet and dry years, which for the Swedish supply of hydro power corresponds to ± 16 TWh. In terms of total annual production capacity, this means a span between 156 TWh and 188 TWh for the power-producing firms. In order to study how both the level and the spread of electricity market prices are affected by the meteorological conditions, under different assumptions concerning the competitive environment, two additional types of scenarios are included. Thus, a dry year with 25 % less precipitation and a wet year with 25 % more precipitation than a normal year are added to the scenarios.

2.6.1 Price formation in a deregulated electricity market

As one would expect the market price is lower in a year when the supply of hydro power is large than in a normal year, in the perfectly competitive case. Correspondingly, the market price is higher than normal when precipitation is low, as can be seen in Table 2.9. This is also the outcome for the Cournot case as well as for the price leader and market share cases. Obviously it is the case in general that large amounts of precipitation put a downward pressure on the market price, and vice versa for small amounts of precipitation.

¹³ Another factor that may influence the competitive environment is a phaseout of nuclear power. This follows similarly from the fact that nuclear capacity is unevenly distributed among the power-producing firms. Thus, a phaseout will affect the marginal costs of each firm differently, which in turn may influence strategy choices. A possible nuclear phaseout is however beyond the scope of this study and is not discussed further in this chapter.

Table 2.9 Equilibrium prices for years with different precipitation.

(All prices in öre/kWh)	Normal year	Dry year (-25% Hydro)	Wet year (+25% Hydro)
Perfectly competitive case	15.1	16.6	14.3
Cournot case	24.5	26.5	21.3
Price leader case	20.8	23.4	18.7
Market share case	17.5	21.0	15.1

Note: All figures are before losses and prices are excluding V.A.T. and electricity tax per kWh.

In the price leader case, the leading firm (VATT) makes an effort to maintain the market price level for a normal year also in a wet year. This does not succeed entirely, but is attempted by means of an even greater cut-back in nuclear power production by VATT during a wet year. This means that VATT substitutes hydro power for nuclear power when precipitation is large. When VATT is assumed instead to compete for market shares, the electricity price remains relatively low but fluctuates substantially between wet and dry years. This is mainly due to the fact that VATT dominates the market and because it has a relatively large share of hydro power in its portfolio of production units, is more sensitive to variations in precipitation than a firm with a smaller proportion of hydro power.

2.6.2 Profit levels and market shares from different strategies

From Table 2.10 it can be seen that the structure of a firm's portfolio of production units greatly influences how its profit level is affected by variations in precipitation. Firms with a relatively low proportion of hydro capacity benefit from low precipitation, whereas years with high levels of hydro capacity are clearly beneficial for the more exclusively hydro power firms such as GRAN.

Table 2.10 Computed profit, quantity and market share levels in the perfectly competitive case in years with different precipitation.

Firms in the model	Profit		Quantity (TWh)		Market share (%)	
	Dry year	Wet year	Dry year	Wet year	Dry year	Wet year
VATT	99	106	79.1	85.0	53.2	52.8
SYD	107	101	29.5	25.8	19.8	16.0
STOCK	105	102	10.2	10.9	6.9	6.8
GULL	98	106	8.0	9.3	5.4	5.8
STOR	95	108	6.3	8.2	4.2	5.1
SKAND	100	105	3.3	4.0	2.2	2.4
SKELL	86	114	2.5	3.8	1.7	2.4
GRAN	83	117	1.9	3.1	1.3	1.9
KORS	94	111	1.3	1.7	0.9	1.1
Fringe	93	111	6.7	9.1	4.5	5.7

This is also reflected in the market shares, since firms with production portfolios based on hydro power gain market shares during wet years at the expense of firms with smaller proportions of hydro capacity. With respect to profits, it can be seen that a firm like GRAN, which has its entire production capacity based on hydro power, is quite sensitive to how the weather turns out. Firms with a more diversified production capacity experience much less fluctuation in their profits as a result of variations in the level of precipitation.

A similar pattern for profits is present in the Cournot case. As can be seen in Table 2.11, wet periods are profitable times for producers that base their electricity production primarily on hydro power. Obviously firms with a small proportion of hydro capacity will gain more from the high price level during a dry year than from the increased capacity resulting from a wet year. The reason is naturally that they only experience a small increase in their capacity but are faced with a substantial drop in the market price at which all their output can be sold.

Table 2.11 Computed profit, quantity and market share levels in the Cournot case in years with different precipitation.

Firms in the model	Profit		Quantity (TWh)		Market share (%)	
	Dry year	Wet year	Dry year	Wet year	Dry year	Wet year
VATT	120	113	49.2	51.9	42.2	39.8
SYD	201	169	26.1	25.8	22.4	19.8
STOCK	203	179	10.7	11.9	9.2	9.1
GULL	185	179	8.4	10.1	7.2	7.8
STOR	172	177	6.5	8.3	5.6	6.4
SKAND	185	178	3.4	4.1	2.9	3.1
SKELL	145	179	2.5	3.8	2.2	2.9
GRAN	140	180	2.0	3.1	1.7	2.4
KORS	172	183	1.4	1.8	1.2	1.4
Fringe	159	186	6.5	9.5	5.6	7.3

As pointed out in the previous section, the increase in price level in the Cournot case compared with the perfectly competitive case, during a normal year, is primarily due to a cut-back in output by VATT. This is evidently the case for both dry and wet years as well, as is clear from Tables 2.10 and 2.11. As expected, this cut-back in production implies a significant reduction of VATT's market share. The strategy involved in the Cournot case forces VATT to give up market shares to its competitors in order to maintain a high mark-up.

For the price leader case, where VATT supplies the residual demand while its competitors are assumed to produce at their capacity, the outcome similarly reveals that VATT holds back its output and correspondingly has a relatively low market share both in dry and wet years. The profit levels are lower than in the Cournot case but the general pattern remains the same. This means that firms with a relatively low proportion of hydro capacity have lower profits in wet years than in dry years, and vice versa for firms with a production portfolio that is dominated by hydro power.

Table 2.12 Computed profit, quantity and market share levels in the price leader case in years with different precipitation.

Firms in the model	Profit		Quantity (TWh)		Market share (%)	
	Dry year	Wet year	Dry year	Wet year	Dry year	Wet year
VATT	107	100	50.8	53.2	40.8	38.1
SYD	190	155	32.4	34.3	26.1	24.6
STOCK	174	150	10.8	11.9	8.7	8.5
GULL	158	151	8.4	10.1	6.8	7.2
STOR	149	151	6.5	8.2	5.2	5.9
SKAND	159	151	3.4	4.1	2.7	2.9
SKELL	126	155	2.5	3.8	2.0	2.7
GRAN	123	157	1.9	3.1	1.5	2.2
KORS	150	156	1.3	1.7	1.1	1.2
Fringe	134	155	6.3	9.2	5.1	6.6

In the final case, when VATT is assumed instead to compete for market shares, the picture is different. Here, VATT's output level is as high as possible. In a wet year this, means as much as 85 TWh, as can be seen in Table 2.13. In consequence, VATT's market share is well above 50 % in both wet and dry years. One interesting observation is that VATT's profit levels are higher in this case than when VATT assumed the role of price leader. In addition, the profits of the other firms are lower in this case than in any other case apart from the first, perfectly competitive one. This implies that VATT is relatively better off in this case than in any of the alternative cases.

Table 2.13 Computed profit, quantity and market share levels in the market share case in years with different precipitation.

Firms in the model	Profit		Quantity (TWh)		Market share (%)	
	Dry year	Wet year	Dry year	Wet year	Dry year	Wet year
VATT	130	113	67.2	85.0	51.1	54.4
SYD	140	108	22.4	24.8	17.0	15.9
STOCK	154	106	10.8	10.9	8.2	7.0
GULL	139	111	8.4	9.2	6.4	5.9
STOR	135	108	6.8	7.8	5.2	5.0
SKAND	149	101	3.7	3.8	2.8	2.4
SKELL	114	100	2.5	3.1	1.9	2.0
GRAN	111	100	2.0	2.5	1.5	1.6
KORS	139	100	1.4	1.5	1.1	1.0
Fringe	119	107	6.4	7.9	4.9	5.1

While VATT increases its market share, the outcome is the opposite for SYD. This follows from the assumptions concerning the behavior of the other firms. They are assumed to consider changes in their own output only and to take the output of their competitors as given when deciding on optimal production levels. Since, in this market share case, SYD is the dominant firm pursuing this strategy, the result is that SYD cuts back on its production in order to increase the mark-up, which results in lost market shares.

It can be concluded that in general, it is the smaller firms that will gain most under the assumptions forming the alternative cases. This is obvious since although it is VATT that cuts back significantly on production in the price leader and the Cournot cases, the benefits from the resulting increases in the price of electricity affect all producers. It is also clear that fluctuations in precipitation affect the profits of firms differently. This stems from the differences in the composition of the firms' portfolios, and especially the varying proportions of hydro capacity. This in turn means that the strategies preferred in different meteorological conditions can vary from firm to firm, due to differences in the blend of production capacity available.

2.7 Choice of strategy

One way of studying the issue of strategy choices is to view the situation in the electricity market as a game between the dominant firm VATT and the rest of the firms. It can be observed from the previous results that for VATT, profits, output levels and market shares are all quite sensitive to the strategy the firms follow. For the other firms, it is primarily profits that are sensitive to the strategy in question, and not so much output levels or market shares. For VATT this can be displayed as in Table 2.14, where profit, output level and market share are shown for all four cases computed earlier.

Table 2.14 Computed profit, quantity and market share levels for VATT in the different market cases.

Firms		Other firms, except Fringe	
		0	-1
VATT	0	Profit: 123 Output: 50.3 TWh Share: 41.4 %	Profit: 106 Output: 52.2 TWh Share: 40.0 %
	-1	Profit: 120 Output: 76.1 TWh Share: 52.6 %	Profit: 100 Output: 82.7 TWh Share: 53.1 %

If the management of VATT takes only profits into account, it is clear from Table 2.14 that the preferred strategy is the one that corresponds to a conjectural variation term equal to 0, regardless of what strategy the other firms are to follow. This means that depending on the other firms' actions, the outcome will be either the Cournot case or the price leader case from among the previous scenarios. If VATT, from the point of view of profit, can be assumed to prefer the strategy where the conjectural variation term is equal to 0, the interest then turns towards the preferred strategy of the other firms. In Table 2.15 the computed profit levels for three of the other firms are displayed in the four different cases. In order to avoid an

unreasonably large table, only SYD, GULL and GRAN are included here. It can be verified from the previous sections that the computed profits of these firms are reasonably representative for all the other firms.

Table 2.15 Computed profit levels for SYD, GULL and GRAN in the different market cases.

Firms		Other firms, except Fringe	
		0	-1
VATT	<i>Conjectural variation term</i>		
	0	<u>Profit:</u> SYD: 185 GULL: 190 GRAN: 169	<u>Profit:</u> SYD: 171 GULL: 155 GRAN: 140
	-1	<u>Profit:</u> SYD: 121 GULL: 121 GRAN: 117	<u>Profit:</u> SYD: 100 GULL: 100 GRAN: 100

From Table 2.15 it is clear that regardless of which strategy is chosen by VATT, the preferred strategy of the other firms is when the conjectural variation term is equal to 0 for all of them. Thus, from the point of view of profit, it is evidently the strategy that corresponds to the Cournot case that is preferred by all the firms in the market.

As mentioned earlier, for VATT, the strategy with a conjectural variation term equal to 0 means a significant drop in output in order to maintain the price mark-up. As can be seen in Table 2.16, this is also the case for SYD, although on a smaller scale. Apparently SYD is large enough to adjust its output in order to influence the price. Correspondingly, SYD loses market shares when this strategy is chosen, whereas the smaller firms maintain their market shares regardless of strategy, as seen in Table 2.17. The fact that SYD holds back production when the strategy chosen assumes a conjectural variation equal to 0, implies in this case, that SYD in addition to VATT, has a surplus of capacity that may be sold in another market.

Table 2.16 Computed output levels for SYD, GULL and GRAN in the different market cases.

Firms		Other firms, except Fringe	
	<i>Conjectural variation term</i>	0	-1
VATT	0	<u>Output (TWh):</u> SYD: 24.4 GULL: 9.3 GRAN: 2.5	<u>Output (TWh):</u> SYD: 33.4 GULL: 9.3 GRAN: 2.5
	-1	<u>Output (TWh):</u> SYD: 24.1 GULL: 8.8 GRAN: 2.5	<u>Output (TWh):</u> SYD: 28.0 GULL: 8.6 GRAN: 2.5

As for VATT, the drop in market share is quite large compared with what SYD experiences. This may be an intriguing issue when choosing which strategy to pursue. First of all, there is the question of what to do with the capacity that is held back. If it can be sold at a reasonable price to customers in some other market without influencing the regular market price, it has been shown that VATT's profit level is well in line with that of other firms. If this is not possible, VATT has to endure a lower profit level than its competitors and still be the firm that carries most of the burden of maintaining the mark-up.

In a longer perspective, it may be in VATT's interest to refrain from some of its short-run profits, especially if it is difficult to find somewhere to sell its surplus power, and in return to maintain its market share. What this implies is that VATT could be tempted to follow the strategy that corresponds to a conjectural variation equal to -1, especially if it were almost certain that the other firms would choose a strategy where this term is equal to 0. The reason for this is that in this case (the market share case) VATT only loses a little in terms of profit level, but manages to maintain its market share. This might be especially tempting for VATT if lost market shares are difficult to regain. That the other firms would follow the strategy that implies this outcome is not too unrealistic, given that their computed profit levels are higher

for the strategy where the conjectural variation term is equal to 0, regardless of which of the strategies VATT chooses.

Table 2.17 Computed market share levels for SYD, GULL and GRAN in the different market cases.

Firms		Other firms, except Fringe	
	<i>Conjectural variation term</i>	0	-1
VATT	0	<u>Market share (%):</u> SYD: 20.0 GULL: 7.7 GRAN: 2.1	<u>Market share (%):</u> SYD: 25.3 GULL: 7.1 GRAN: 1.9
	-1	<u>Market share (%):</u> SYD: 16.7 GULL: 6.1 GRAN: 1.7	<u>Market share (%):</u> SYD: 18.0 GULL: 5.5 GRAN: 1.6

The inclination for VATT to choose a strategy other than the Cournot or price leader strategy may be even stronger when the computed profit levels from the sensitivity analysis are considered. As can be seen in Table 2.18, VATT's profit levels are the same in a wet year for both strategies, assuming that the other firms always choose a strategy where the conjectural variation is equal to 0. Since this strategy dominates in both dry and wet years for most of the other firms, this is a possible outcome. In a dry year, the profit level is actually higher when VATT chooses the strategy with the conjectural variation equal to -1 rather than equal to 0, if we still assume that the other firms choose 0.

Table 2.18 Computed profit levels for VATT, SYD, GULL and GRAN in the different market cases in years with different precipitation.

Firms		Other firms, except Fringe			
		0		-1	
	<i>Conjectural variation term</i>				
VATT	0	<u>Dry year</u> <i>Profit:</i> VATT: 120 SYD: 201 GULL: 185 GRAN: 140	<u>Wet year</u> <i>Profit:</i> VATT: 113 SYD: 169 GULL: 179 GRAN: 180	<u>Dry year</u> <i>Profit:</i> VATT: 107 SYD: 190 GULL: 158 GRAN: 123	<u>Wet year</u> <i>Profit:</i> VATT: 100 SYD: 155 GULL: 151 GRAN: 157
	-1	<u>Dry year</u> <i>Profit:</i> VATT: 130 SYD: 140 GULL: 139 GRAN: 111	<u>Wet year</u> <i>Profit:</i> VATT: 113 SYD: 108 GULL: 111 GRAN: 100	<u>Dry year</u> <i>Profit:</i> VATT: 99 SYD: 107 GULL: 98 GRAN: 83	<u>Wet year</u> <i>Profit:</i> VATT: 106 SYD: 101 GULL: 106 GRAN: 117

However, as can be seen in Table 2.18, the strategy with a conjectural variation term equal to 0 is not dominant for all other firms in both wet and dry years. GRAN would prefer to choose -1 as a response to VATT's strategy with a conjectural variation term equal to -1 during a wet year.

All in all this indicates that it is not self-evident that the Cournot case is the outcome that will dominate in all possible cases, although it seems to be a strong candidate. There are two reasons for doubt. First, VATT may decide against holding back so much power, in order to maintain its market share instead, especially since the drop in profit level may not be substantial. Second, given the fluctuations in precipitation that face this industry, it is even more uncertain which of the strategy combinations that dominates for all of the firms.

2.8 Concluding remarks

From the computed results and from the point of view of profit, it is evident that it is the Cournot case that is the dominant strategy in most outcomes. This would then be the answer to the question how the firms would like the market to be formed. However, it may not be this simple. As discussed in the preceding analysis, the dominant firm VATT stands to lose substantial market shares if it pursues this strategy and cuts back accordingly on its output. This may prove to be an inoptimal strategy in the longer run if it turns out that these market shares can only be regained at a high cost to the firm. If this is the case it might be unwise for VATT to cut back on production.

In a future study it would be interesting to have an estimate of the costs associated with the gaining and maintenance of market shares. With reasonable data it would be possible to expand the model in order to include a trade-off between cutting back on output for the sake of higher profits, and simultaneously losing market shares. This might then shed some light on this 'dilemma' for a dominant firm.

Appendix 2.A

Price elasticity

$$\eta = -0.5$$

Table 2.A.1 Computed production in years with different precipitation.

	Normal year	Dry year	Wet year
(All numbers in TWh)		(-25% Hydro)	(+25% Hydro)
Perfectly competitive case	155.7	148.7	160.9
Cournot case	121.4	116.5	129.6
Price leader case	132.0	124.4	139.7
Market share case	144.6	131.5	156.2

Note: All figures are before losses.

Chapter 3

Competition and Market Power Over Time: The Case of a Deregulated Swedish Electricity Market

3.1 Introduction

The Swedish wholesale electricity market is characterized by a very high degree of concentration on the seller side. This market structure is a potential threat to the main purpose of the deregulation, which is to increase competition on the electricity market and achieve lower market prices. In Andersson and Bergman (1995) and in Chapter 2 this was analyzed in a static numerical model, and it was shown that electricity prices may indeed be higher after a deregulation. One counter measure to this that is often brought forward in the debate is to split state-owned Vattenfall, with a market share close to 50 %, into two separate companies. The intention of this would be to reduce concentration and increase the level of competition.

The purpose of this chapter is to model and analyze the development of competition and market power over time in the wholesale market for electricity in Sweden. The main issue concerns whether a dominant firm can maintain a high mark-up over time. Or stated differently, is it necessary to split Vattenfall in order to achieve a high degree of competition in the deregulated Swedish electricity market. This will be explored quantitatively as the relation between the Cournot-equilibrium price, and the size distribution of firms in the market. The key feature is to use dynamic oligopoly theory in a numerical model of the deregulated Swedish electricity market.

The remainder of the chapter is structured as follows. In the next section different aspects of competition over time are discussed. This is followed by a presentation of the model and a section describing the empirical background. The paper proceeds with a discussion of the price development in a deregulated electricity market based on the results from different scenarios. In the final section are some concluding remarks then made.

3.2 Competition over time in the electricity market

In the static case it is clear how to formulate the competitive equilibrium. When time enters and the firms have a possibility to add new production capacity the problem is more difficult. In this chapter focus is set on the issue of market power and competition over time in the electricity market. As will become clear when the model is presented in a subsequent section, the competitive environment is formulated as Cournot competition at each time period, with perfect foresight assumed for all firms in the market. Given the difficulties that exist when a dynamic problem is analyzed, it is vital to study important aspects of relevant literature concerning competition over time and dynamic oligopolies. Particularly in order to establish the existence of possible alternatives to the formulation used here.

3.2.1 Supergames

Over time the firms in an industry meet not only once, but many times in the market. It is reasonable to assume that the firms that are active in the market are part of a game with an almost infinite time horizon, something that is also taken for granted by the firms. Over time each firm has an opportunity to observe the actions taken by the competitors, and how this affects the market price and the market shares. This in turn creates a situation to which each firm may react as they see fit.

The game that corresponds to this is called a repeated game or a supergame (see Tirole (1988)). In a basic form the market can be assumed to consist of two firms that produce a homogenous product. Both firms produce at the same marginal cost, c . There are no capacity constraints and the lower-price firm thus gets the sales of the entire market, and when the price charged is the same from both firms they share the market equally. In principle the basic static game is then repeated T times where T can be finite or infinite. Firm f 's profit at time t when it charges P_f and its competitor asks P_{-f} is written $\pi^f(P_f, P_{-f})$. The objective of both

firms is to maximize the present discounted value of its profits Π_f , which is defined as

$$\Pi_f = \sum_{t=0}^T \delta_t \pi^f(P_f, P_{-f}), \quad (1)$$

where the discount factor is $\delta_t = \left(\frac{1}{1+r}\right)^t$, with r denoting the interest rate.

At each time t the firms then choose the prices at which they sell their output. This choice is simultaneous for the firms. There is no physical link between the time periods, which implies that the competitors choice of price in the previous period is already irrelevant when the present price choice is to be made. The price strategies are to form a perfect equilibrium¹⁴ where, for any history of prices, firm f 's strategy from date t and onwards maximizes the present discounted value of profits given the strategy of the competitor from that time on.

The time horizon is first assumed to be finite, i.e. $T < +\infty$. The equilibrium of this dynamic price game is found by 'backward induction'. The question is then how the firms choose the prices in the last period T , given the history of the prices. Since the prices before do not affect the profits earned in period T , the outcome is to maximize the profit as if the problem was a static one. Thus, each firm should maximize $\pi^f(P_{fT}, P_{-fT})$, given the price of the competitor, and the equilibrium in period T is then the Bertrand one for any history of prices:

$$P_{fT} = P_{-fT} = c. \quad (2)$$

For period $T-1$ the reasoning follows a similar path. Since the choices of price at T are independent of the outcome at $T-1$, it follows that choices made at $T-1$ can be made as if this was the last period. Thus, firms choose the competitive outcome also in $T-1$, regardless of the history of prices up to this time period. This procedure of backward induction can then be repeated for all t , all the way back to period 0. The outcome is the Bertrand solution for all periods and the dynamic element does not contribute anything to this model.

If $T = +\infty$ instead, i.e. the horizon is infinite, the outcome can be quite different. Although it can be verified that the Bertrand equilibrium repeated infinitely is still an outcome of the game. This can be illustrated by first letting each firm choose a price that is equal to its marginal cost in each period t . This is done regardless of the previous history of the game. If

¹⁴ The perfect equilibrium requires that strategies are in equilibrium whatever the location (subgame) in the game tree and not only along the optimal path. (See Tirole (1988)).

the competing firm does charge a price equal to c like this, no firm can do better than to charge c by itself, and the outcome is the Bertrand solution for all periods.

However, the interesting part of the story is that the repeated Bertrand equilibrium is not the only equilibrium in this case. To see this, first let the monopoly price on this market be denoted by P^m . One set of symmetric strategies for each one of the firms can then be to charge P^m in period 0. The firms will furthermore charge P^m in each period t , given that both firms in every period prior to t have charged P^m . If not, the choice is to set price equal to marginal cost for all future periods. These strategies, called trigger strategies, are called so since one single deviation by one firm triggers the end of the cooperation.

The trigger strategies are an equilibrium if the discount factor is sufficiently high. Consider the two firms which each charge P^m . They will then each earn half the monopoly profit in every period. If one firm deviates slightly from this price it can earn the maximum profit of π^m during the period it deviates. Or rather, it can earn approximately the π^m by undercutting the monopoly price slightly. However, if this is done, it will earn zero profits forever after. Hence, if the trigger strategies are to be equilibrium strategies the following has to be fulfilled;

$$\frac{\pi^m}{2}(1 + \delta + \delta^2 + \dots) \geq \pi^m \quad (3)$$

which is the case for $\delta \geq \frac{1}{2}$. This is a formalization of tacit collusion (Tirole (1988)). Thus, a firm that undercuts the monopoly price gains substantially during the period it deviates, but by undertaking this action it destroys all collusion in later periods, i.e. the firms turn to the strategy of choosing the competitive outcome forever, which as indicated earlier is an equilibrium. It should be pointed out that the collusion in this case is enforced through a purely non-cooperative mechanism.

One feature as well as a possible problem with this game is the existence of many other equilibria. The implications of the reasoning above is that any price between the competitive price and the monopoly price may constitute an equilibrium price, as long as the discount factor is above $\frac{1}{2}$. This feature is one part of a general result known as the Folk theorem. For

this repeated game the Folk theorem states that any pair of profits (π^f, π^{-f}) such that

$$\left. \begin{array}{l} \pi^f > 0 \\ \pi^{-f} > 0 \\ \pi^f + \pi^{-f} \leq \pi^m \end{array} \right\} \quad (4)$$

constitute an equilibrium payoff in each period for δ sufficiently close to 1. One interpretation of this is that when δ is close to 1, everything is an equilibrium in this model. This is the case since aggregate profits can never exceed the monopoly profits and equilibrium profits for a firm can never be negative since a firm always can charge a price above marginal cost or exit the market. The Folk theorem has been proved by for example Friedman (1971).

Thus, the basic insights of multiperiod or supergame theory for oligopoly is that if the market situation is repeated for an infinite number of periods the situation may develop where the firms in the industry settle on a cartel price, and the reason for not breaking the implicit agreement is the insight of future losses incurred when the defecting firm is retaliated against by the competitors. In general the collusive behavior depends monotonically on the discount factor that firms apply to profits earned in the future and the number of competing firms that are present in the industry. This follows from the fact that a high discount factor reduces the value of retaliation in the future while a large number of firms implies a smaller market share for each of the firms taking part in the collusion. This in turn increases the value of defection from the cartel price and thus weakens the incentives to collude.

The effect from the number of firms in the industry is however two-fold: on the one hand it is critical for the market shares at each price, and on the other hand it is the basis for total industry capacity which in turn is highly important for how far a price may fall following retaliation action from the other firms. The magnitude of the potential price drop is of course important for the strength of the collusion. If, for example, there is an industry in which total capacity is slightly above monopoly capacity, then the collusive forces are weak. This follows since the most forceful retribution the other firms can realize is to produce at full capacity forever, and since this action will render profits close to the shared monopoly profits the threat of future price competition triggered by defection is weak in this case. This implies that defection can be expected and in equilibrium the outcome would be competition. If the number of firms in this case is increased the threat imposed by the rest of the firms may be large enough to outweigh the one period gains obtained by defecting. Brock and Scheinkman (1985) have also shown that under the case of capacity constraints, changes in the number of firms may have a non-monotone effect on cartelisation and the resulting price.

3.2.2 Dynamic oligopoly

One issue with the theory of supergames is that it is difficult to distinguish a single equilibrium in this type of models. In Maskin and Tirole (1987) an alternated theory of dynamic oligopoly is discussed. (See also Maskin and Tirole (1988a and 1988b).) Their approach consist of a class of sequential duopoly games where the commitments of the firms are formalized. In the basic version of these games the time horizon is discrete and infinite and the firms move alternatingly. This implies that when a firm chooses its action, it has perfect knowledge about the present actions taken by its competitor. The point of having the firm locked-in to its actions for two periods is intended to capture a firm's short-run commitments.

Competition between the two firms takes place in discrete time with an infinite horizon. At each time t firm f 's profit π^f is a function of the two firms' current quantities, X_f and X_{-f} , but not of time, thus, $\pi^f = \pi^f(X_{f,t}, X_{-f,t})$. That firms choose quantities can be thought of as a choice of capital or capacity as discussed in Kreps and Scheinkman (1983), where the quantity game is considered as a reduced form of a more complex game where long-run competition is carried out through choices of capital and short-run competition through prices.

The present value of firm f 's profit is

$$\Pi^f = \sum_{s=0}^{\infty} \delta_s \pi^f(X_{f,t+s}, X_{-f,t+s}) \quad (5)$$

where δ_s is the discount factor. Firm f 's strategy is assumed to depend only on the payoff-relevant state, implying those variables that directly enter the profit function of the firm. This implies that the strategies are assumed to be Markov. The object is to establish a pair of dynamic reaction functions, $R_f(\cdot)$ and $R_{-f}(\cdot)$, that constitute a Markov perfect equilibrium. Perfection requires that, regardless of the state at the start, a firm's dynamic reaction function will maximize the present value of the discounted profits given other firms' reaction functions.

The implication is that if the locked-in current quantity of firm f is X_f , the competing firm reacts by choosing quantity $X_{-f} = R_{-f}(X_f)$ in order to maximize the present discounted value of its profits, given that both the competing firms then will move according to R_f and R_{-f} .

The present discounted profit of firm f when it reacts to its competitors quantity choice X_{-f} is then denoted by $V^f(X_{-f})$. Furthermore, let the present discounted profit of firm f , when it is locked into quantity X_f and its rival reacts, be denoted by $W^f(X_f)$. The equilibrium conditions that follow for firm f are:

$$V^f(X_{-f}) = \max_X [\pi^f(X_f, X_{-f}) + \delta W^f(X_f)], \quad (6)$$

$$R_f(X_{-f}) \text{ maximizes } [\pi^f(X_f, X_{-f}) + \delta W^f(X_f)], \quad (7)$$

$$W^f(X_f) = \pi^f(X_f, R_{-f}(X_f)) + \delta V^f(R_{-f}(X_f)), \quad (8)$$

and can also be written similarly for the competing firm $-f$. Note that the time subscripts are excluded since the dynamic reaction functions themselves are time independent. In Tirole (1988) it is shown that the reaction curves are downward sloping, which is important for the results that follow.

To find the equilibrium reaction functions the system of equations (6) - (8) must be solved. The process of finding a differentiable solution, if it exists, is generally difficult. After differentiation of equation (8) and taking the first order conditions of equation (6) some substitutions leads to a system of difference-differential equations for the two reaction functions (Tirole (1988)). This system is generally hard to solve, unless the profit functions are quadratic. In those cases with a profit function such as:¹⁵

$$\pi^f = X_f(d - X_f - X_{-f}) \quad (9)$$

there exists a reasonably simple solution where the reaction function of each firm is linear in its competitors quantity. The solution is also the limit of each firm's reaction function at any date when the horizon is finite but tends to infinity (see Tirole (1988)).

When $\delta=0$ the firms behave according to the static reaction functions and the steady state is the Cournot solution.

¹⁵ Let the price be denoted by $P = d - X_f - X_{-f}$, where $d > 0$, $P > 0$ and d represents the difference between the intercept of the demand curve and the marginal cost.

For firm f the reaction function then is

$$R_f(X_{-f}) = \frac{d}{2} - \frac{X_{-f}}{2} \quad (10)$$

which maximizes the profit function and is written similarly for firm $-f$. For $\delta > 0$ the firms do not only consider current profits but do also take its competitors future reactions into account. In each period the firm that is about to move takes both these factor into consideration. Suppose that the other firm is at the Cournot level. If the first firm that is about to move then increases its output slightly above the Cournot level it will have practically no effect on short run profit. However, since the reaction functions are downward sloping the increase will induce the other firm to cut back its output in the period that follow, which in turn has a positive effect on long run profits for the first firm. The bottom line of this argument is that the first firm has an incentive to choose a higher output in a dynamic setting than in a static. It can be said to act as a 'Stackelberg leader'. Since this is true for the other firm as well, the result is output above the Cournot level. Thus, the dynamic model is more competitive than the static case for $\delta > 0$.

3.2.2.1 Adjustment costs

So far there have been no costs associated with changes in output for the firms. The next step is to introduce output related adjustment costs beyond the variable cost already embodied in π^f . The cost depends on the current choice of output, $X_{f,t}$, and the previous output, $X_{f,t-2}$. Let this cost be written $A^f(X_{f,t}, X_{f,t-2})$. Since the output $X_{f,t-2}$ has an influence on the current profit at time t for firm f , the payoff-relevant state is $(X_{-f,t-1}, X_{f,t-2})$. The corresponding Markov strategy at time t is

$$X_{f,t} = R_f(X_{-f,t-1}, X_{f,t-2}). \quad (11)$$

It is then shown in Maskin and Tirole (1987) that with symmetric and quadratic profit functions and adjustment costs, and for any discount factor, the steady state output in this dynamic model tends to the static Cournot output as the adjustment cost becomes large.

The intuition of this is the following: Suppose that both firms start near the Cournot outcome. When one firm then increases its output slightly, as in the previous case without the adjustment costs, the other firm cuts back its own output. The catch is that the larger the

adjustment cost, the smaller is the decrease in output, and thus the smaller is the gain for the first firm. As adjustment costs get larger, the effect has a more important influence on short run profits.

3.2.2.2 Endogenous timing

One alternative to the exogenous setting where firms move alternately is to endogenize the relative timing of the firms' moves. Maskin and Tirole (1987) discuss an extension of the model above where the assumption that one firm only can move in odd numbered periods, and the other firm only in even numbered periods, is abandoned. The firms are instead allowed to move in any period, but if it chooses to move, it remains committed to the choice for two periods. Thus, in any period when a firm is not committed it can change its output, or decide not to move at all. If it chooses not to produce at all it is free to move at any future time.

The firm's payoff is in this setting affected by both whether the other firm is committed to a quantity level at the current time and if this is the case, what the quantity is. As pointed out by Maskin and Tirole (1987), the Markov strategies then depend on a two-dimensional payoff relevant state.

As argued by Maskin and Tirole (1987) it can be shown, at least for cases when the future is not too heavily discounted, that any Markov Perfect Equilibrium involves reaching a steady-state regardless of the starting point, and that a steady state will consist of simultaneously moving firms that are choosing the Cournot quantities.

The intuition for this comes from the following: When firms move alternately they are induced to choose an output level that is higher resulting in lower profits, as discussed in a previous section, than were they to move simultaneously. This in turn provides the firms with a joint incentive to move simultaneously instead of alternately. However, firms may for some reason get 'stuck' in an alternating mode due to the fact that one firm chooses to wait for the other to move first at the beginning of the time horizon. If there is little discounting the gain from moving simultaneously will however dominate the cost for each firm of conducting a switch from alternating to simultaneous mode. This implies that the simultaneous mode will ultimately prevail.

Finally, in an effort to conclude this theoretical overview, it can be pointed out that it is obviously not a clear-cut issue which formulation of a dynamic oligopoly problem that should

be used. Although the theoretical findings displayed here are not entirely supportive of using Cournot competition in a dynamic oligopoly, this alternative has not been entirely refuted either. It can in particular be noted that no model has turned out as an alternative candidate to the Cournot model, which is the tool planned to be used in this chapter. Thus, having concluded this from the theoretical overview, the decision is to use Cournot competition in the numerical analysis.

3.3 The model

The model will be presented in two main steps. First, the demand for electricity and the production costs for the power producing firms are described in order to establish an electricity price and the marginal costs for the firms. Second, the conditions for profit maximization are established given the competitive environment. The model is a dynamic partial equilibrium model designed to endogenously determine the market clearing prices of electricity.

The planning horizon in the model extends through the year 2030. For computational reasons it is convenient to use five-year time intervals. The initial period refers to the electricity market during the period 1991 through 1995. This five-year time period ($t=1$) will generally be referred to in terms of the year 1991, which is the first in the period. The initial period is also the "base year" around which the model is calibrated. The year 1991 is chosen as base year since this year is a good description of the Swedish electricity market prior to the deregulation.

The way the periods are set, the first five-year period belongs to the time prior of the deregulation (1991 - 1995). From day one of period two the market has been deregulated, since this occurred on January 1st in 1996. This implies that the computed first year of period two, which is 1996, has actually already passed. However, since only one of the five years belonging to period two has passed this should not constitute a problem. With the help of more observations, i.e. the data for the rest of the years in period two, it may be possible to improve the calibrations further in a future version of the model.

3.3.1 Electricity demand

The demand for electricity over time is in general terms dependent on the initial stocks of all electricity using equipment and all future prices. To include all this information would be an ideal way to model electricity demand over time. However, due to the absence of proper data, and in addition the fact that focus in this study is on market power on the producer side, the modeling of the demand for electricity is simplified.

In the discussion in Chapter 1 it was indicated that the market demand for electricity consists of the sum of the demands of a large number of relatively small consumers. This in turn implies that there is no market power on the demand side of the market. Given the assumptions that all other product and factor prices are given, that the price elasticity of electricity demand is constant and equal to η and that there is complete separability in time, the demand function is written

$$E_t = E_0 e^{\psi t} \left(\frac{P_t^E}{P_0^E} \right)^{\eta}; \quad (12)$$

where E_t is total electricity consumption and P_t^E is the market price of wholesale electricity at time t . The $e^{\psi t}$ denotes the growth in electricity demand over time, which in turn is driven by the growth in national income.¹⁶ The subscript 0, of the variable in question, denotes the exogenous value from before the deregulation of the market.

The electricity consumed in the market is mainly produced by the F domestic firms and is to a small extent imported. The sum of domestic production and imports equals demand in equilibrium. Since imports are relatively small during a normal year (see Chapter 1), and are not the main issue in this study, they are omitted in order to simplify the analysis.

¹⁶ The national income, denoted by Y_t , which in the model grows at an exogenous annual rate, is normalized to one for the base year, and is the driving force in the model, as the demand for electricity is assumed to grow at the rate of the income, subject to the income elasticity, denoted by ε . For the expression in (12) this can be

written; $\left(\frac{Y_t}{Y_0} \right)^{\varepsilon} = \left(\frac{Y_0 e^{\theta t}}{Y_0} \right)^{\varepsilon} = e^{\psi t}$, where ψ then is the product of the income growth, θ , and the elasticity, ε . The subscript 0 denotes the exogenous value from the base year.

By denoting production in firm f at time t by X_t^f , the equilibrium condition is written:

$$E_t = \sum_{f=1}^F X_t^f. \quad (15)$$

By substituting equation (15) in (14) an expression for the equilibrium price as a function of domestic production is obtained. This inverse demand function is written

$$P_t^E = P_0^E \left(\frac{\sum X_t^f}{E_0 e^{\psi t}} \right)^{1/\eta}, \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8 \quad (16)$$

where P_t^E is the wholesale market price of electricity at time t . The price in the model is the wholesale electricity price and it is assumed that the electricity price is the market clearing price of one-year contracts for delivery of electric power to customers with a representative time-of-use profile for their electricity use over the year.

3.3.2 Production costs

The firms in the model act independently of each other and seek to maximize their profits. A firm is defined as a "portfolio" of production units and three main categories of production capacity are distinguished. The first category consists of nuclear and hydro power capacity. This is the dominant production category since, as was shown in Chapter 1, hydro and nuclear power together account for more than 95 % of power production in Sweden. The second category of production capacity is an aggregate of fossil-fueled plants, ranging from units of combined heat and power production that are in operation for more than 4,000 hours per year, to gas-fueled units that are operated for only a few hours per year. The third category of capacity, is new capacity added to the existing stock of production units. In a general sense this could be of any of the existing types of production capacity. However, due to politically determined constraints one can rule out new capacity from nuclear or hydro power and in order to simplify the modeling the choice is limited to gas condense in.

As in the previous chapter the major individual electricity producing firms are identified in the model in order to replicate the real world properly. Of these firms the nine largest are modeled as active players, while the remaining small power producers are aggregated into one group, which is assumed to adapt production to the prevailing wholesale market price of electric power. The assumed behavior of the fringe firms is an important issue in the dynamic setting

and will be discussed further in sections 3.3.3 and 3.5. The firms that are present in the model and their respective portfolios of production units at the start of the analysis were discussed in Chapter 1. For the reader's benefit the data concerning the firms are also displayed in Table 3.1.

Table 3.1 Electricity producing firms and their production capacity.

Firms in the model	Hydro power TWh/year	Nuclear power TWh/year	Fossil power TWh/year	Capacity TWh/year
VATT	35.7	40.4	15.0	91.1
SYD	6.9	17.1	10.6	34.6
STOCK	3.2	4.8	4.0	12.0
GULL	3.9	3.6	1.6	9.1
STOR	3.9	2.1	1.2	7.2
SKAND	1.6	1.2	0.8	3.6
SKELL	2.6	0.4	-	3.0
GRAN	2.4	-	-	2.4
KORS	0.9	0.3	0.3	1.5
Fringe	5.1	-	2.6	7.7
Total	66.2	69.9	36.1	172.2

Note: The capacity data are based on the situation in 1991.

Source: NUTEK (1991, 1992 and 1995)

The first production category, which consists of nuclear and hydro power capacity, is denoted in the model by i , with $i=1,2$ for hydro and nuclear, respectively. The second category of production capacity, which is an aggregate of fossil fueled-plants, is denoted by j . The third and final production category, which represents capacity in new plants, is denoted by n .

The output from plants in category i in firm f at time t , is denoted X_t^{fi} , and output from plants in category j , or the other type of existing plants is denoted X_t^{fj} , while output from new plants is denoted X_t^{fn} . The total output for firm f , X_t^f , is given by

$$X_t^f = \sum_{i=1}^2 X_t^{fi} + X_t^{fj} + X_t^{fn}, \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8 \quad (17)$$

The utilization of the different plants is determined by cost minimization considerations at a given level of firm output, i.e. the plants are run in the order of increasing marginal costs. The

cost of production in category i units at time t is defined by

$$C_t^f = c^i X_t^f; \quad X_t^f \leq K_t^f; \quad \text{for } f=1,2,\dots,F, \forall i \text{ and } t=1,2,\dots,8 \quad (18)$$

where c^i is a firm-independent unit cost of operation and output is limited to available capacity K_t^f .

For units in category j the cost function is

$$C_t^f = a^j X_t^f + b^j \left(\frac{X_t^f}{K_t^f} \right)^\phi X_t^f; \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8 \quad (19)$$

where a^j is the fuel and other operating costs per unit of output in the cheapest type of combined heat and power production units, $a^j + b^j$ is the corresponding cost in oil-fired condensing power plants and K_t^f is installed production capacity. In order to approximate the significantly higher production cost of gas turbines, which have to be made use of at times when all other production capacity at the firm's disposal is already fully utilized, the exponential parameter ϕ is introduced as a positive number greater than unity. Thus, for low values of X_t^f the marginal cost is close to a^j , and at X_t^f equal to K_t^f it is equal to $a^j + b^j$, and then increases rapidly as X_t^f grows.

For production in new units in category n , the cost function is

$$C_t^{fn} = d^n X_t^{fn}; \quad X_t^{fn} \leq K_t^{fn}; \quad \text{for } f=1,2,\dots,F, \text{ and } t=1,2,\dots,8 \quad (20)$$

where d^n is the operating cost per unit of output of a new gas-fired condensing power plant and where the output X_t^{fn} is limited to available capacity K_t^{fn} .

The firms have to invest in capacity of category n before it can be taken into operation and the cost of this investment is represented by the function

$$CI_t^{fn} = g_t^n I_t^{fn}; \quad \text{for } f=1,2,\dots,F, \text{ and } t=1,2,\dots,8 \quad (21)$$

where g_i^n is the investment cost per unit of new capacity¹⁷, I_i^{fn} , that is taken into operation by firm f .¹⁸

At a given point in time a firm's installed production capacity is defined by the amount of installed capacities of respective category and the investments that have been made in new capacity in the previous period, i.e.

K_i^{fn} and K_i^{ff} are exogenously given

and (22)

$$K_i^{fn} = \sum_{\tau=1}^{t-1} I_{\tau}^{fn}; \quad \text{for } f=1,2,\dots,F, \quad t=1,2,\dots,8 \text{ and } \forall i.$$

From equation (22) it is clear that investments made at $t-1$ will not become available for production until time t . The intention of this is to capture the lag that is present between the investment decision and the availability of the unit associated with investments in large power production plants. As for the depreciation rate of the installed capacity, it is assumed to be equal to zero net after productivity growth.

The next step is to determine the cost function for the firm. A firm's marginal cost of production, $\partial C_i^f / \partial X_i^f$, as well as its utilization of available capacity is determined by cost minimization considerations. Thus, each individual firm allocates output between the different production units in the portfolio in order to minimize its costs at each given level of output. The firm's cost for producing X_i^f can be regarded as a solution to the intertemporal

¹⁷ The issue of remaining terminal values of installed capacity at the end of the time horizon is dealt with by decreasing the cost of the investment over time according to an annuity calculation. This implies that investments made late in the time horizon of the model and which actually have an economic life beyond the time span of the model are compensated for by a lower investment cost. In terms of equation (21) this implies that the investment cost g_i^n decreases, following an annuity calculation, as time approaches the end of the time horizon of the model.

¹⁸ The investment in production capacity is at the outset defined in power terms and has to be transformed to energy terms to fit the model. From this follows $I_i^{fn} = IW_i^{fn} h^n$, where the factor h^n represents the number of hours a unit of category n is in operation per time period, which is included to transform the investment in power terms, IW_i^{fn} , to energy terms.

minimization problem.

$$\begin{aligned}
C^f(X_1^f, \dots, X_8^f, I_1^{fn}, \dots, I_8^{fn}; K_t^{f1}, K_t^{f2}, K_t^{fj}) = \\
\min_{X_t^f, X_t^{fj}, X_t^{fn}, I_t^{fn}} \sum_{t=1}^8 \left(\frac{1}{1+r}\right)^t \left[\sum_{i=1}^2 C_t^{fi} + C_t^{fj} + C_t^{fn} \right] + \sum_{t=1}^8 \left(\frac{1}{1+r}\right)^t CI_t^{fn} \\
s.t. \quad \sum_{i=1}^2 X_t^{fi} + X_t^{fj} + X_t^{fn} \geq X_t^f \quad ; \lambda_t^f \\
\quad -X_t^{fi} \geq -K_t^{fi} \quad ; \lambda_t^{fi}; i=1,2 \\
\quad -X_t^{fn} \geq -\sum_{\tau=1}^{t-1} I_\tau^{fn} \quad ; \lambda_t^{fn} \\
\quad X_t^{fi}, X_t^{fj}, X_t^{fn}, I_t^{fn} \geq 0 \quad ; i=1,2
\end{aligned} \tag{23}$$

The Lagrange function is then written

$$\begin{aligned}
L = \sum_{t=1}^8 \left(\frac{1}{1+r}\right)^t \left[\sum_i c^i X_t^{fi} + a^j X_t^{fj} + b^j \left(\frac{X_t^{fj}}{K_t^{fj}}\right)^\phi X_t^{fj} + d^n X_t^{fn} \right] \\
+ \sum_{\tau=1}^8 \left(\frac{1}{1+r}\right)^\tau g_\tau^n I_\tau^{fn} + \left(\frac{1}{1+r}\right)^t \mu_t^f \left(X_t^f - \sum_i X_t^{fi} - X_t^{fj} - X_t^{fn} \right) \quad ; i=1,2; f=1,2,\dots,F, \tag{24} \\
+ \left(\frac{1}{1+r}\right)^t \mu_t^{fi} (X_t^{fi} - K_t^{fi}) + \left(\frac{1}{1+r}\right)^t \mu_t^{fn} \left(X_t^{fn} - \sum_{\tau=1}^{t-1} I_\tau^{fn} \right)
\end{aligned}$$

with C_t^{fi} , C_t^{fj} , C_t^{fn} and CI_t^{fn} defined from equations (18), (19), (20) and (21) respectively and the current shadow values defined as

$$\left. \begin{aligned} \left(\frac{1}{1+r}\right)^t \mu_t^f &= \lambda_t^f \\ \left(\frac{1}{1+r}\right)^t \mu_t^{fi} &= \lambda_t^{fi} \\ \left(\frac{1}{1+r}\right)^t \mu_t^{fn} &= \lambda_t^{fn} \end{aligned} \right\} \quad \text{for } f=1,2,\dots,F, t=1,2,\dots,8 \text{ and } i=1,2, \tag{25}$$

with the discount rate denoted by r .

The first-order Kuhn-Tucker conditions then yield

$$\left. \begin{array}{l} c^i - \mu_t^f + \mu_t^{fn} \geq 0 \\ X_t^{fn} (c^i - \mu_t^f + \mu_t^{fn}) = 0 \end{array} \right\} \quad \text{for } i=1,2, f=1,2,\dots,F \text{ and } t=1,2,\dots,8. \quad (26)$$

$$\left. \begin{array}{l} a^j + b^j \left(\frac{X_t^{\beta}}{K_t^{\beta}} \right)^{\phi} - \mu_t^f \geq 0 \\ X_t^{\beta} \left(a^j + b^j \left(\frac{X_t^{\beta}}{K_t^{\beta}} \right)^{\phi} - \mu_t^f \right) = 0 \end{array} \right\} \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8. \quad (27)$$

$$\left. \begin{array}{l} d^n - \mu_t^f + \mu_t^{fn} \geq 0 \\ X_t^{fn} (d^n - \mu_t^f + \mu_t^{fn}) = 0 \end{array} \right\} \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8. \quad (28)$$

and

$$\left. \begin{array}{l} g_t^n - \sum_{\tau=t+1}^T \mu_{\tau}^{fn} \geq 0 \\ I_t^{fn} \left(g_t^n - \sum_{\tau=t+1}^T \mu_{\tau}^{fn} \right) = 0 \end{array} \right\} \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8. \quad (29)$$

The Lagrange multiplier μ_t^f can be interpreted as the firm's marginal cost, thus $\mu_t^f = \partial C_t^f / \partial X_t^f$. The multiplier denoted by μ_t^{fn} , which is associated with the first capacity constraint, can be interpreted as a firm-specific scarcity rent on firm f 's production capacity in category i . Similarly can μ_t^{fn} be viewed as a firm-specific scarcity rent on production capacity in new units in category n . The expressions in (29) thus ensure correct investment decisions on behalf of the individual firms. In conclusion the first order Kuhn-Tucker conditions above ensure that the firms utilize their production capacity in merit order and only run a specific technology, or add new capacity, when it is cost-effective.

3.3.3 Profit maximization

Total production, and then also the price level, is in the model determined by profit maximization behavior on the part of the producers as well as by the competitive environment. The firms are assumed to maximize the present discounted value of their profits. Obviously one major concern in this study is the level of concentration among the power producers and the related issue of market power. By assuming Cournot competition in the model, the possible influence on prices from the market power exercised by the dominating firms will be evident in the analysis.

As discussed in a previous section it has been shown by Maskin and Tirole (1987) that if a firm's strategy is assumed to depend only on the payoff-relevant state, then regardless of which discount factor that is used, the steady-state equilibrium converges to the static Cournot outcome as adjustment costs increase in size. Given this and the focus on market power in this study it is reasonable to use Cournot competition in the present model. Thus, focus in the numerical applications will be on the Cournot equilibrium.

The profit maximizing condition with respect to production level and the corresponding complementarity condition, which together ensure correct production decisions on behalf of the individual firms are written:

$$\left. \begin{aligned} P_t^E + X_t^f \frac{\partial P_t^E}{\partial X_t} - \frac{\partial C^f}{\partial X_t^f} &\leq 0 \\ X_t^f \left(P_t^E + X_t^f \frac{\partial P_t^E}{\partial X_t} - \frac{\partial C^f}{\partial X_t^f} \right) &= 0 \end{aligned} \right\} \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8 \quad (30)$$

where X_t denotes total output of all firms at time t . For the group of firms in the fringe the assumption is that they behave as price takers in this case. Thus, the computed Cournot equilibrium in the numerical analysis is a Cournot equilibrium with a competitive fringe.

In addition to the Cournot equilibrium a competitive equilibrium based on short run marginal cost pricing is established for comparative reasons. The price is determined as the short-run marginal cost or as the price that clears the market given the existing capacities. The profit maximizing condition with respect to the production level can be expressed as the standard competitive market price-equal-to-marginal-cost condition. Together with the corresponding

complementarity condition this is written:

$$\left. \begin{array}{l} P_t^E - \frac{\partial C^f}{\partial X_t^f} \leq 0 \\ X_t^f \left(P_t^E - \frac{\partial C^f}{\partial X_t^f} \right) = 0 \end{array} \right\} \quad \text{for } f=1,2,\dots,F \text{ and } t=1,2,\dots,8. \quad (31)$$

This equilibrium is in a sense a lower bound for how far down fierce competition may push the market clearing price on the electricity market and can thus also be viewed as a perfectly competitive equilibrium.

This completes the description of the model. It is empirically implemented by means of production cost and capacity distribution data from the Swedish power industry, and calibrated to the actual situation in 1991. The model is solved using GAMS software (see Brooke et.al. (1988)), and a standard run takes approximately 5 minutes on a Pentium PC.

3.4 The base year

For the numerical examples in the sections that follow the model is calibrated around a base year. This year is chosen as to capture the situation in the "old" Swedish electricity market, prior to the reform. This implies that VATT is assumed to act as price leader in the market and to apply marginal cost pricing subject to a rate of return constraint. This means in turn that the base year equilibrium price corresponds to VATT's marginal cost of production plus a mark-up based on the required rate of return.¹⁹ Thus, the model has been calibrated such that the first period in the model corresponds to the 1991 level of electricity production, both in total and for individual firms, as well as the wholesale market price of electricity in 1991. The year 1991 has been chosen as the base year since it can be viewed as the last normal year prior to the deregulation.

Estimates of the variable costs associated with the different sources of old and existing power generation plants that are used in the model, have been discussed in Chapter 1, but are also shown in Table 3.2.

¹⁹ The price formation in the model is based on one-year contracts for customers with a representative time-of-use profile of their electricity use over the year.

Table 3.2 Technologies and variable costs of electricity production.²⁰

Technologies	Cost/kWh
Hydro power	1.5 Öre ²¹
Nuclear power	7 Öre
Fossil power	9-22 Öre

Source: NUTEK(1991 and 1992), SOU 1995:140 and Nordhaus (1995)

The cost for a new plant is assumed to be the same regardless of which firm that makes the investment. Thus, there are no entry barriers from the point of view that incumbents could have a cost advantage when it comes to investments in new power. The costs for new production capacity are presented in Table 3.3.

Table 3.3 Costs for new production capacity.

	Investment costs SEK/kW	Cost/kWh
Gas condense	6 500 SEK	19 öre

Source: SOU 1995:140 and Nordhaus (1995)

Note: The costs are in 1995 SEK.

One assumption made regarding the investments in new capacity is that they are divisible in the model and not 'lumpy'. This means that investments made by the firms in the model are not restricted by some minimum plant size or other limitation in this context. This is of course not a perfect representation of real world investments in new power plants, but since new plants are available in relatively small sizes, at least when compared to many of the existing nuclear and hydro plants, this appears to be a reasonable assumption.

²⁰ Since one-year contracts are used as products the costs are the short run variable costs plus semi-variable costs, such as maintenance etc. The semi-variable costs are added in order to correctly represent the costs that the firms are facing during the duration of a one-year contract.

²¹ 100 öre = 1 SEK = 0.13 US \$, October 3, 1997.

It has been pointed out before, but it is important to mention that the supply of hydro power can vary up to ± 16 TWh between years depending on actual precipitation. From this it is clear that the annual production capacity of the power producing firms vary accordingly, which for the capacity situation in 1991 would imply a span between approximately 156 TWh and 188 TWh. The data presented for the base year are based on the situation in 1991 when total domestic power production was 142.5 TWh.

Two other important factors are the discount rate used in the model and the growth of income in the economy, which is the driving force in the model. The discount rate used throughout the model is 5 %. This level is chosen mainly as it is perceived to capture the agents time preference reasonably well, but also for comparative reasons since 5 % appears to be the discount rate that is used in many other studies on the subject of energy analysis. See for example NUTEK (1994).

As for the growth rate of the national income, it is assumed to be equal to 1.5 % annually, over the time horizon of the model. This growth rate is slightly below what was used in for example NUTEK (1994) and Nordhaus (1995). As a form of sensitivity analysis on this factor, scenarios with an annual growth of 2.5 % are also computed. The growth of the demand is determined by the income elasticity, which is assumed to be equal to 1.0.

3.5 Price development on a deregulated electricity market

3.5.1 Market power over time

In the base year calibration the production of electricity is 142.5 TWh and the equilibrium price is 18 öre/kWh. This is one natural norm of comparison for the goal of lower market prices and increased competition following the deregulation of the Swedish electricity market. If an outcome with a perfectly competitive equilibrium is assumed for the wholesale electricity market, the result is indeed a lower market price. The perfectly competitive equilibrium price, with given production capacities, is 15.1 öre/kWh which indicates a possibility for a price reduction after deregulation.

The first year of the model can be viewed as a result of a static model with exogenous production capacities. If the model is solved for a Cournot equilibrium, the result is a significantly higher price in 1991 when the production capacities are given. As can be seen in

Table 3.5 the level of electricity production in 1991 is considerably lower in the case of a Cournot equilibrium when compared to a perfectly competitive equilibrium. The reason for this is mainly that production is held back by the largest firm VATT in the Cournot equilibrium. In exact terms what VATT does is reducing its nuclear power production from 40 TWh in the perfectly competitive case to only 14 TWh in period 1 in the Cournot case.

Since the perfectly competitive equilibrium price is equal to the common marginal cost of production for all the firms, it can be considered as a lower bound for what the price can be reduced to when competition on the electricity market is fierce. The results for 1991 indicates that with given production capacities it is possible that the price on a deregulated market may indeed be higher than before and that firms may achieve a high mark-up through strategic behavior. This has also been shown in Andersson and Bergman (1995) and in the previous chapter.

One question is then whether a dominant firm on the deregulated electricity market is able to maintain this high mark-up as time goes by. Over time it is possible for competitors to enter the market with units of new production capacity. This can be either in the form of incumbents adding new plants to the portfolio of existing plants, or new entrants to the electricity market. In addition to this, there is the annual growth of the economy increasing the demand for electric power and thus making the share of excess production capacity existing at the time of the deregulation, smaller and smaller.

Table 3.4 Computed equilibrium prices for different years on the electricity market.

Economic growth: 1.5%/year	1991	2000	2010	2020
Perfectly competitive equilibrium (Öre/kWh)	15.1	19.4	26.0	27.8
Cournot equilibrium with competitive fringe (Öre/kWh)	24.5	25.7	27.7	27.8

Note: The prices are before losses and excluding V.A.T. and electricity tax per kWh.

In Table 3.4 it is shown that the gap between the Cournot and the perfectly competitive equilibrium price levels narrows over time; from a difference of around 9 öre/kWh in 1991,

the gap has disappeared entirely by the year 2020. This outcome where the gap disappears is a result that stems from the assumption that the firms in the competitive fringe are acting as price takers. If the fringe firms instead were modeled as individual agents behaving as Cournot players, a gap between the price levels in the perfectly competitive equilibrium and the Cournot equilibrium would remain over time. This latter case could be said to correspond to having some barrier of entry to the market with Cournot competition. This means there could be an additional cost assumed for firms that enter the market as new power producers. The size of the computed gap between the perfectly competitive case and the Cournot case then depends on the structure of the market, the available technology and how large the additional cost of entry is.

Table 3.5 Total production computed for different years on the electricity market.

(All numbers in TWh)	1991	2000	2010	2020
Perfectly competitive equilibrium	155.7	156.5	160.5	173.5
Cournot equilibrium with competitive fringe	121.4	133.4	149.5	173.5

If the results are examined more closely it can also be found that by the year 2020 the largest firm VATT is running all the nuclear power that was held back in 1991. Thus, according to the model it can be stated that the possibilities for a dominant firm to maintain a large mark-up on a deregulated Swedish electricity market exist in the short run but shrink in the longer run.

The results so far are based on an annual economic growth equal to 1.5 %. If this growth were to be faster and instead was 2.5 % per year, this would have an impact on the possibilities for the large firms to maintain their market power. In Table 3.6 the computed equilibrium prices from a scenario with faster economic growth are displayed.

Table 3.6 Computed equilibrium prices for different years on the electricity market.

Economic growth: 2.5%/year	1991	2000	2010	2020
Perfectly competitive equilibrium (Öre/kWh)	15.1	24.7	27.8	27.8
Cournot equilibrium with competitive fringe (Öre/kWh)	24.5	27.7	27.8	27.8

Note: The prices are before losses and excluding V.A.T. and electricity tax per kWh.

As can be seen in Table 3.6 a faster economic growth reduces the ability for a dominant firm to maintain a large mark-up over some time. It is the case that the prices approach each other even in the shorter run. Thus, a fast economic growth is good in a pro-competitive sense on the electricity market. It is however clear that a faster economic growth leads to exhaustion of the existing capacities at an earlier stage than when the economy grows slowly. This in turn implies that although the competitive environment is tougher on the electricity market, the prices experienced by the consumer are not necessarily lower.

3.5.2 The case of a Swedish nuclear phaseout

In the Swedish parliament there has been a decision taken which in effect means that the nuclear power is to be phased out. Although the time frame for this phaseout has been uncertain, one year that has been in focus as the final year is 2010. Given this decision of a nuclear phaseout and the large share of nuclear production capacity in Sweden it is interesting to analyze how this would affect the price formation in the electricity market.

In order to analyze this the model is adjusted in such a way that all the nuclear capacity is phased out by the year 2010. The reduction in nuclear capacity is set up such that the phaseout is initialized already by the year 2000 in order to spread the phaseout over some time to resemble how this process is planned in the real world.

As can be seen in Table 3.7 the possibility for a dominant firm to maintain a large mark-up is reduced in this case. The computed equilibrium prices when the Swedish nuclear power is being phased out are quite similar to the results from Table 3.6, with the fast economic

growth. The similarity can be explained by the fact that the need to invest in and to use new and more expensive capacity is realized at an earlier stage either when the economy grows faster or when the nuclear capacity is phased out.

Table 3.7 Computed equilibrium prices for different years on the electricity market when nuclear power is phased out by the year 2010.

Economic growth: 1.5%/year	1991	2000	2010	2020
Perfectly competitive equilibrium (Öre/kWh)	15.1	25.6	27.7	27.8
Cournot equilibrium with competitive fringe (Öre/kWh)	24.5	25.7	27.7	27.8

Note: The prices are before losses and excluding V.A.T. and electricity tax per kWh.

3.5.3 One firm having an investment cost advantage

So far all firms have been able to build new capacity at the same cost. Although it is reasonable to assume that the technology that is used as new capacity in the analysis is standard and available to all firms it may be argued that certain firms can increase their capacity at a lower cost than others. This may for example stem from experience with the technology, or better and more efficient internal routines. In addition, it is possible that an incumbent firm may have a better knowledge about the process of acquiring the proper permissions necessary for the construction of new power producing plants.

In the analysis this is introduced by assigning a 10 % decrease in the investment costs for one of the firms. It may be argued that the firm being largest at present can be the one that has a cost advantage over the other firms. Thus, one case is based on the assumption that VATT has a competitive edge over the other firms. In addition two cases are computed where SYD and GRAN each have a cost advantage. This is done to be able to evaluate possible differences that are due to the market structure and the relative size of the firm with the competitive edge. The computed prices for the perfectly competitive equilibria when one of the firms VATT, SYD or GRAN have the cost advantage, are displayed in Table 3.8.

Table 3.8 Computed perfectly competitive equilibrium prices for different years on the electricity market when one firm has an advantage in investment costs.

Economic growth: 1.5%/year	1991	2000	2010	2020
<u>Firm with competitive edge</u>				
VATT	15.1	18.9	23.4	26.8
SYD	15.1	18.9	23.4	26.8
GRAN	15.1	18.9	23.4	26.8

Note: All prices are in öre/kWh and are before losses and excluding V.A.T. and electricity tax per kWh.

As can be seen in Table 3.8 the computed prices are the same for each year regardless of which firm that is the single one having the competitive edge. It is also clear that the price levels for the later periods are lower than the price level computed without the cost advantage. If the results are studied closely it turns out that although the prices are the same the cases are quite different regarding which firm that makes the investments. In each of the three cases it is found that all investments in new capacity are made by the firm with a cost advantage.

For the Cournot equilibrium it is perhaps a bit surprising to observe that the pattern is the same concerning the computed prices. As can be observed in Table 3.9 this implies that the prices are lower than when no cost advantage was present, and in addition that the prices are the same regardless of which firm is the one with the competitive edge. One may have expected that the results would be different for the case where a small firm has the cost advantage compared to when a dominant firm is the one with a competitive edge.

Table 3.9 Computed Cournot equilibrium prices for different years on the electricity market when one firm has an advantage in investment costs.

Economic growth: 1.5%/year	1991	2000	2010	2020
<u>Firm with competitive edge</u>				
VATT	24.5	24.8	26.7	26.8
SYD	24.5	24.8	26.7	26.8
GRAN	24.5	24.8	26.7	26.8

Note: All prices are in öre/kWh and are before losses and excluding V.A.T. and electricity tax per kWh.

Note: Cournot equilibrium with competitive fringe.

However, the explanation for this becomes more clear when the market shares of the firms are studied for the different cases. As can be seen in Tables 3.10, 3.11 and 3.12 the fact that a firm has a cost advantage greatly influences the development over time of the computed market shares.

Table 3.10 Computed market shares for different years on the electricity market when VATT has an advantage in investment costs.

Economic growth: 1.5%/year	1991	2000	2010	2020
VATT	41.4 %	46.8 %	47.1 %	49.3 %
SYD	20.0 %	19.3 %	18.2 %	16.8 %
GRAN	2.1 %	1.9 %	1.7 %	1.5 %

Note: The market shares are computed for the case of Cournot equilibrium with a competitive fringe.

Table 3.11 Computed market shares for different years on the electricity market when SYD has an advantage in investment costs.

Economic growth: 1.5%/year	1991	2000	2010	2020
VATT	41.4 %	39.9 %	40.6 %	40.7 %
SYD	20.0 %	25.4 %	27.7 %	32.0 %
GRAN	2.1 %	1.9 %	1.7 %	1.5 %

Note: The market shares are computed for the case of Cournot equilibrium with a competitive fringe.

In all the three computed cases of Cournot equilibrium it is primarily VATT that is responsible for maintaining the mark-up in the industry. The price level which VATT is able to sustain is dependent on the cost for new capacity. With a cost advantage present this is what determines the level of the prices regardless of which firm this advantage is benefiting. When VATT has a cost advantage it may maintain the mark-up while gaining market shares since it is the firm that first finds it profitable to expand its capacity. For the other two cases

VATT still maintains the mark-up but loses market shares since another firm with the cost advantage finds it profitable to be the first to expand.

Table 3.12 Computed market shares for different years on the electricity market when GRAN has an advantage in investment costs.

Economic growth: 1.5%/year	1991	2000	2010	2020
VATT	41.4 %	39.9 %	40.6 %	40.7 %
SYD	20.0 %	18.5 %	17.3 %	15.3 %
GRAN	2.1 %	6.7 %	10.4 %	16.6 %

Note: The market shares are computed for the case of Cournot equilibrium with a competitive fringe.

As can be seen from the Tables 3.10, 3.11 and 3.12 the effect on market shares of a 10 % advantage on investment costs is quite large. In the case where an initially small firm such as GRAN has the advantage, it turns out that by 2020 it has expanded from only 2 % of the market to around 16 %. For the firm SYD, which has a market share of about 20 % at the outset, the result of not having a cost advantage is a drop in market shares to about 16 %. On the other hand, if it is the case that SYD is the only firm with a cost advantage, it instead increases its market shares substantially, going from about 20 % to around 32 %.

In conclusion it can be argued that a cost advantage for one firm will clearly result in a downward pressure on the mark-up in the industry. In addition it is interesting to observe that this is the case regardless of which firm that is in control of the cost advantage. The real effects from this can instead be seen in the development of market shares over time.

3.6 Concluding remarks

From the results of the model it is shown that it is possible for a dominant firm to maintain a high mark-up over some time. However, in the longer run this possibility shrinks as the market grows, which reduces the relative power of a dominant firm. The rate at which this is realized in the model depends to a large extent on the annual economic growth. It is possible for competitors to expand on the market, either in the form of incumbents that are increasing their production possibilities or entirely new producers entering the market. It is however

important to point out that this process could take 10 to 20 years in the model, depending on how fast the economic growth is assumed to be. In this context it could also be pointed out that in a study by Gilbert and Harris (1984) it has been shown that for competition in the presence of lumpy investments, it is possible that a result which resembles Bertrand competition can occur, even with only two firms.

In the case of the Swedish electricity market, the planned phaseout of nuclear power is also a factor that may put pressure on the possibilities for a dominant firm to maintain a high mark-up. Since a phaseout would hasten the need for investments in new capacity this reduces the relative power of the dominant firm. This pro-competitive effect is perhaps unintentional from a policy point of view, but is never-the-less present in the results of the analysis. In addition it should be pointed out that although the phaseout may promote competition it will still result in a relatively high price level.

Finally, a few words concerning the question whether to split Vattenfall into two separate companies in order to reduce its dominant position in the Swedish electricity market. From the results of the model it can be argued in favor of a split in the short run perspective, but in the longer run the concern for the market position of Vattenfall becomes less of an issue. However, this is a complex issue that is not analyzed from all possible sides here. A split would indeed be a very large measure and the consequences should be investigated further, especially from a welfare point of view, since there are significant transaction costs involved with a break-up of the firm.

Appendix 3.A - Parameter values

Real income growth

$$\theta = 1.5 \%$$

Discount rate

$$r = 5 \%$$

Demand elasticities

$$\text{Price elasticity:} \quad \eta = -0.5$$

$$\text{Income elasticity:} \quad \varepsilon = 1.0$$

Depreciation rate of installed capacity

$$\text{Net after productivity growth:} \quad \delta = 0$$

Chapter 4

Market Power and Competition in a Deregulated Nordic Electricity Market

4.1 Introduction

In addition to the deregulation of the Swedish electricity market there was another major electricity market reform that came into effect in January 1996. This was the integration of the Norwegian and Swedish markets into one 'Nordic' deregulated electricity market. The Norwegian electricity market was deregulated already in 1991. Although the joint Nordic market still only consists of two countries, the intention is that Finland as well as Denmark will follow suit and in the near future join Norway and Sweden. In Finland new legislation has been passed in this direction, indicating that it is only a matter of time until the Finnish electricity market is integrated with the Swedish and Norwegian.

For the idea of one market to materialize it is of course necessary that transmission possibilities exist between the two previously national electricity markets. In the Nordic case transmission lines already exist since there has been a successful co-operation between the countries to better utilize the national power systems. However, after deregulation the existing lines have at times been bottlenecks in the system, creating price differences between Norway and Sweden. The main grid lines in the joint Swedish and Norwegian electricity market have been modeled by Håden (1997), where primarily the existence of short run bottlenecks due to technical differences between the two national systems have been examined in a perfectly competitive environment.

The purpose of this chapter is to study how competition is formed and how market power may be maintained in a joint Swedish and Norwegian wholesale market for electric power. The interest in this follows from the main argument in favor of the deregulation brought forward by the authorities, which is that deregulation means increased competition in the electricity market and thus lower market prices. However, as noted in previous chapters, a real threat to this outcome is the high degree of concentration among the Swedish power producers. In Andersson and Bergman (1995) it was also shown that electricity prices may even be higher after than before deregulation of the Swedish electricity market. One remedy for this may arguably be an expansion of the Swedish market into a Nordic market, whereby the market concentration decreases considerably from a Swedish point of view.

The tool used to study competition and market power in a joint Swedish and Norwegian wholesale market for electric power is a numerical model of the deregulated Nordic electricity market. The main question asked concerns to what extent it is possible for a dominant firm in one country to maintain its market power in an integrated Nordic market. This will be studied quantitatively as the relation between the Cournot equilibrium price and the size distribution of firms in the two countries, taking the potential bottlenecks in the transmission lines on the border between the two countries into account.

The remainder of the chapter is structured as follows. The next section contains a brief description of the power production in Norway and Sweden. This is followed by a presentation of the model and a discussion of competition in the electricity market. The empirical background is then described in the section thereafter. The chapter proceeds with a discussion of price development in a deregulated Nordic electricity market, based on the results from different scenarios. Some concluding remarks are then made in the final section.

4.2 The Norwegian and Swedish electricity markets

Given that Sweden and Norway are neighboring countries their systems for power production have quite different profiles. In Sweden the production of electricity is dominated by two main sources, namely hydro power and nuclear power. These two sources each make up about one half of total annual electricity production. In Norway the geographical prerequisites for hydro power are even better than in Sweden. This is one major factor behind the development of an electricity production system which almost to 100 % consists of hydro power. To rely entirely on hydro power for electricity production naturally makes a system vulnerable for

large variations in the precipitation level. As noted in a previous chapter, annual supply of hydro power can vary as much as $\pm 25\%$, when measured as deviations from a normal year.

The difference in composition of the electricity production systems in the two countries has had the consequence that during wet years, with excess supply of hydro power, there is usually a net flow of electricity from Norway to Sweden. During dry years the opposite is normally the case, with the net flow of electricity going from Sweden to Norway, when measured over the entire year.

Another aspect in which the two countries are different concerns the level of concentration among the power producing firms. For Sweden this issue has been discussed in previous chapters. For an overview of the largest producers in Sweden and their power production, see Table 1.5 in Chapter 1. In Norway the largest firm Statkraft, which is state owned, account for only a bit more than 25 % of the market. The remaining firms are smaller than this and the Norwegian electricity market is characterized by a large number of relatively small producers. The largest Norwegian producers and their power production are displayed in Table 4.1.

Table 4.1 Electricity production in Norway by different producers in 1992.

Firm	Production (TWh)	Share of total (%)
Statkraft	30.6	27.3
Hydro Energi	10.0	8.9
Oslo Energi	7.7	6.9
Bergenshalvøens Kraftselskap	5.5	4.9
Lyse Kraft	5.4	4.8
Trondheim Elektrisitetsverk	3.2	2.9
Vest-Agder Energiverk	2.7	2.4
Hafslund Energi	2.5	2.2
Nord-Trøndelag Elektrisitetsverk	2.3	2.1
Skienfjordens Kraftselskap	2.3	2.1
Kristiansand Energiverk	2.2	2.0
Aktieselskabet Tyssefaldene	2.1	1.9
Akershus Energiverk	2.0	1.8
Aust-Agder Kraftverk	1.9	1.7
Other firms	31.5	28.1
Total production	111.9	100.0

Source: NORDEL (1994) and Samkjøringen av kraftverkene i Norge (1992).

Prior to the deregulation and integration of the markets the Swedish and Norwegian electricity markets were part of a co-operation among the Nordic countries called Nordel. The main purpose of this was to use the connections between the countries' main grids to optimize the production system over both the year, as well as between night and day. The driving force behind this has been the difference in production structure between the Nordic countries, ranging from one country with purely hydro power, via one country with a mixture of hydro and thermal power, to a country with a national system dominated by thermal power production. The trade of electric power between Sweden and Norway amounted to Swedish imports of 6.9 TWh in 1995, which was an increase from 4.5 TWh the year before. The Norwegian imports of electricity from Sweden was in 1995 equal to 1.2 TWh, which was a decrease from 1994, when the corresponding number was 2.8 TWh. As the trade figures indicate the net amount transmitted is smaller than the turnover, with Sweden being a net importer of electric power from Norway during both 1995 and 1994.

Following the deregulation of the Norwegian electricity market in 1991, the electricity prices in Norway fell significantly. This may primarily have been caused by both a down-turn in the economy and mild weather, which lowered demand at the time, and unusual large amounts of precipitation, creating an extra supply of hydro power. Nevertheless this created expectations of increased competition and lower electricity prices in a deregulated Swedish electricity market as well. However, this outcome has been questioned primarily because of the high degree of concentration on the supply side of the Swedish electricity market. In particular these concerns have been aimed at the size and dominant position of Vattenfall. In light of this it is especially interesting to investigate the effects of an integration of the Swedish and Norwegian electricity markets, since - at least in theory - this larger market should imply a significant dilution of the market power that Vattenfall may exercise.

It is then perhaps somewhat surprising to observe that following the deregulation of the Swedish electricity market and the integration with the Norwegian market on January 1, 1996, the spot price of electricity rose rapidly. It reached levels more than 50 % above the pre-deregulation levels only after a few weeks of trade. Whether this was a result of dominant firms exercising their market power, or only a natural price increase due to the extremely cold winter and dry previous summer and fall, is something that needs to be studied in more detail before any conclusions can be drawn.

From a theoretical point of view it is difficult to point at some straight-forward solution to how prices in a deregulated electricity market may be formed, as has been discussed in earlier chapters. Very crucial for the outcome are the assumptions made concerning the behavior of

the firms in the market, in combination with how influential they are, i.e. how large their respective market shares are. The electricity market is in this sense especially interesting given the technical circumstances that makes the integrated Norwegian and Swedish markets not just one large market, but a market where the individual firms may act in anticipation of how the potential bottlenecks in the transmission system could affect the level of competition.

4.3 The model

The model used is a static partial equilibrium model of the integrated electricity markets in two neighboring countries. It is designed to endogenously determine the market clearing prices of electricity. The presentation of the model is carried out in different steps. First, the demand for electricity and the production costs for the power producing firms are described. This is vital for the establishment of the electricity price and the marginal costs for the firms. Second, the treatment of the transmission possibilities between the markets in the two countries is described. Finally, the competitive environment and different competitive equilibria are discussed.

4.3.1 Electricity demand

The demand for electricity in the market consists of the sum of the demands by a large number of relatively small consumers in each country. This implies that there is no market power on the demand side of the market. Following the assumption that all other product and factor prices are given, the demand function is written

$$E_c = E_c^0 \left(\frac{P_c^E}{P_c^{E0}} \right)^{\eta_c}; \quad c=1,2. \quad (1)$$

where η_c is the price elasticity of electricity demand, E_c is total electricity consumption and P_c^E is the market price of electricity. The subscript c represents either one of the two countries Norway and Sweden. From this follows that the demand for electricity in country c is assumed to only depend on the price of electricity in country c . The superscript 0, of the variable in question, denotes the exogenous value from before the deregulation and/or integration of the markets.

On the electricity market in country c the F_c independent firms compete. The electricity output of firm fc is initially sold to consumers in country c , and when the borders are open for intercountry trade, also to consumers in country c' , where c is not equal to c' . By letting sales be denoted by S and using r as an index for the country of destination of the sales, it holds that

$$X_{fc} = \sum_{r=1}^2 S_{fcr} ; \quad fc=1,2,\dots,F_c. \quad (2)$$

Thus, sales by each firm has to be equal to total production by the firm, which is denoted by X_{fc} .

However, due to transmission losses incurred for the part of the sales that go to the foreign market for each firm the supply of electricity in destination country r is less than the aggregate supply at the firm level, whenever there is trade between the countries. In order to account for this the supply of electricity in country r is written

$$S_r = \sum_{c=1}^2 \sum_{fc=1}^{F_c} (1 - \gamma_{cr}) S_{fcr} ; \quad (3)$$

where total supply of electricity in country r is denoted by S_r and γ_{cr} denotes the transmission loss per unit of sales from country c to country r , with delta $\gamma_{cc} = 0$ indicating that there are no transmission losses for domestic sales.

In equilibrium sales equal demand and by substituting equation (3) in (1) an expression for the equilibrium price as a function of sales is obtained for each country. This inverse demand function is written;

$$P_r^E = P_r^{E0} \left(\frac{S_r}{E_r^0} \right)^{1/\eta_r} ; \quad r=1,2. \quad (4)$$

The price in the model is the wholesale electricity price. It is assumed that the electricity price is the market clearing price of one-year contracts for delivery of electric power to customers with a representative time-of-use profile of their electricity use over the year. Furthermore, there is assumed to be no uncertainty in the model.

4.3.2 Production costs

The firms in the model act independently to maximize their individual profits. A firm is defined as a 'portfolio' of production units and there are two main categories of capacity that are distinguished. The first category consists of nuclear and hydro power capacity. This is the dominant production category since, as was mentioned earlier, hydro and nuclear power together account for more than 95 % of the power production in Sweden, and the power system in Norway consist of almost 100 % hydro power. The second category of production capacity is an aggregate of fossil fueled plants, ranging from units of combined heat and power production which are in operation more than 4,000 hours per year, to gas-fueled units that are operated only for a few hours per year.

The major individual electricity producing firms in Sweden and Norway are identified in the model. Of these firms the nine largest in Sweden and the five largest in Norway are modeled as active players. The remaining small power producers are aggregated into one group for each country, which is assumed to adapt production to the prevailing market price of wholesale electric power. The Swedish firms identified in the model and their respective production capacities were introduced in Chapter 1 and are also presented in Table 4.2 below.

Table 4.2 Electricity producing firms in Sweden and their production capacity.

Firms in the model	Hydro power TWh/year	Nuclear power TWh/year	Fossil power TWh/year	Capacity TWh/year
VATT	35.7	40.4	15.0	91.1
SYD	6.9	17.1	10.6	34.6
STOCK	3.2	4.8	4.0	12.0
GULL	3.9	3.6	1.6	9.1
STOR	3.9	2.1	1.2	7.2
SKAND	1.6	1.2	0.8	3.6
SKELL	2.6	0.4	-	3.0
GRAN	2.4	-	-	2.4
KORS	0.9	0.3	0.3	1.5
S-Fringe	5.1	-	2.6	7.7

Note: The capacity data are based on the situation in 1991.

Source: NUTEK (1991, 1992 and 1995)

For Norway the situation is different compared to Sweden since nearly all electric power is produced by hydro power. Although some other power exists in the Norwegian system it is in the model assumed that all the Norwegian firms produce their electricity in hydro power plants. The data presented in Table 4.3 are based on the situation in 1991.

Table 4.3 Electricity producing firms in Norway and their production capacity.

Firms in the model	Hydro power TWh/year	Capacity TWh/year
STAT	31.6	31.6
HYDRO	10.0	10.0
OSLO	7.7	7.7
BERGEN	5.5	5.5
LYSE	5.4	5.4
N-Fringe	52.7	52.7

Note: The capacity data are based on the situation in 1991.

Source: NORDEL (1994) and Samkjøringen av kraftverkene i Norge (1992).

The first production category, which in the model consists of hydro and nuclear power capacity, is denoted by i , where $i=1,2$ to represent hydro and nuclear, respectively. Output in plants of category i in firm f situated in country c is denoted X_{fci} . The second category of production capacity, which is an aggregate of fossil fueled plants, is denoted by j and output in this second category of plants is denoted X_{fcj} . The total output in firm f in country c , denoted by X_{fc} , is given by

$$X_{fc} = \sum_{i=1}^2 X_{fci} + X_{fcj}; \quad fc=1,2,\dots, F_c. \quad (5)$$

The next step is to define the cost of production for the firm. In units of category i this is defined by

$$C_{fci} = c_i X_{fci}; \quad X_{fci} \leq K_{fci}; \quad i=1,2 \text{ and } fc=1,2,\dots, F_c. \quad (6)$$

where c_i is a unit cost of operation that is firm-independent. In addition output from units of category i is limited to available capacity K_{fci} .

The cost function for units of category j is written

$$C_{fcj} = a_j X_{fcj} + b_j \left(\frac{X_{fcj}}{K_{fcj}} \right)^\phi X_{fcj}; \quad fc=1,2,\dots, F_c. \quad (7)$$

where a_j denotes the fuel and other operating costs per unit of output in the least expensive type of combined heat and power production units. The sum of a_j+b_j is the corresponding cost in oil-fired condensing power plants. In order to approximate the significantly higher production cost prevalent in gas turbines, which have to be taken into use at times when all other production capacity at the firm's disposal is already fully utilized, the exponential parameter ϕ is introduced as a positive number greater than unity. Thus, when production is small and the values of X_{fcj} are low the marginal cost is close to a_j . When production and X_{fcj} are equal to the capacity K_{fcj} the marginal cost is equal to a_j+b_j , and then increases rapidly as X_{fcj} grows.

Each firm allocates output individually between the different production units in its portfolio in order to minimize costs at each given level of output. The cost for the firm of producing X_{fc} can be regarded as the solution to the minimization problem.

$$\begin{aligned} C_{fc}(X_{fc}, K_{fc1}, K_{fc2}, K_{fcj}) &= \min_{X_{fci}, X_{fcj}} \sum_{i=1}^2 C_{fci} + C_{fcj} \\ \text{s. t. } \sum_{i=1}^2 X_{fci} + X_{fcj} &\geq X_{fc} && ; \mu_{fc} \\ -X_{fci} &\geq -K_{fci} && ; \lambda_{fci}; i=1,2 \\ X_{fci}, X_{fcj} &\geq 0 && ; i=1,2 \end{aligned} \quad (8)$$

The Lagrange function is then written

$$\begin{aligned} L = \sum_{i=1}^2 c_i X_{fci} + a_j X_{fcj} + b_j \left(\frac{X_{fcj}}{K_{fcj}} \right)^\phi X_{fcj} \\ + \mu_{fc} \left(X_{fc} - \sum_{i=1}^2 X_{fci} - X_{fcj} \right) + \lambda_{fci} (X_{fci} - K_{fci}); \end{aligned} \quad fc=1,2,\dots, F_c. \quad (9)$$

with C_{fci} and C_{fcj} defined from equations (6) and (7), respectively. The first-order Kuhn-Tucker

conditions then yield

$$\left. \begin{array}{l} c_i - \mu_{fc} + \lambda_{fei} \geq 0 \\ X_{fei}(c_i - \mu_{fc} + \lambda_{fei}) = 0 \end{array} \right\} \quad i=1,2; fc=1,2,\dots,F_c \quad (10)$$

and

$$\left. \begin{array}{l} a_j + b_j \left(\frac{X_{fej}}{K_{fej}} \right)^\phi - \mu_{fc} \geq 0 \\ X_{fej} \left(a_j + b_j \left(\frac{X_{fej}}{K_{fej}} \right)^\phi - \mu_{fc} \right) = 0 \end{array} \right\} \quad fc=1,2,\dots,F_c. \quad (11)$$

The Lagrange multiplier μ_{fc} can be interpreted as the marginal cost of the firm. As for the other multiplier λ_{fei} , which is related to the capacity constraint, it can be interpreted as a firm-specific scarcity rent on the production capacity of category i that is owned and controlled by the firm. These conditions ensure that the firms utilize their production capacity in merit order and only run a specific technology when it is cost-effective.

In conclusion, all this implies that total and marginal costs for the firms are established through the cost functions for the different production categories and the portfolio of production units controlled by the separate firms.

4.3.3 The transmission system

The nodes, or countries, in the model are interconnected by lines which have limits on their maximum power flow capacity, as well as exogenous terms representing the losses. The modeling of the transmission system is simplified compared to the work in Håden (1997) where a system of nodes are modeled in detail in a perfectly competitive environment. In this study the model consists of only two nodes: Norway and Sweden. This simplifies the matter since no considerations have to be made regarding for example loop-flows of power.

Transmission losses are denoted by $\gamma_{cc'}$, as indicated earlier, and are assumed to be linear and exogenous. Given the results observed in Håden (1997) this should not have a dramatic effect on the results in this model with a very simplified transmission system.

There is an exogenous limit on the maximum amount of power that can flow on the line in each direction between the two nodes. The flow on the line across the border depends on the amount of sales that the firms have on the foreign market. In the model there is one intercountry two-way transmission line defined. This line handles the flow of power from Norway to Sweden and from Sweden to Norway. The intercountry gridline is denoted by g , and the use of transmission line g , per unit of sales from country c to country r , is denoted by ω_{gr} . The following constraint then has to be satisfied for each pair of c and r :

$$\sum_{fc} \omega_{gr} S_{fcr} + \sum_{fr} \omega_{gc} S_{frc} \leq TMAX_g ; \quad (12)$$

where $TMAX_g$ is a line specific constant representing the upper limit of power that can flow on the intercountry gridline g . The flow from country c to country r is represented by the first term in equation (12), while the flow going in the other direction is represented by the second term. The main point with this formulation is that the constraint reflects that the need for transmission capacity depends on the net flow over the transmission line.²²

In addition a scarcity rent, denoted φ_g , represents the marginal cost of congestion on the transmission line connecting the countries. This marginal cost is greater than or equal to zero. It is equal to zero when the constraint in (12) is not binding, and may be positive when the constraint is binding. This implies that in equilibrium the following complementarity condition must hold for each pair of c and r :

$$\varphi_g \left(\sum_{fc} \omega_{gr} S_{fcr} + \sum_{fr} \omega_{gc} S_{frc} - TMAX_g \right) = 0 \quad (13)$$

This completes the description of the transmission possibilities in the model of the integrated Nordic electricity market.

²² The restriction $TMAX_g$ is defined as the capacity limit on the intercountry gridline for the duration of the one-year contracts that are priced in the model. The ω_{gr} could be viewed as a way to transform energy to power. The use of this factor becomes more important in a model consisting of more than two countries or regions when there is not only one line by which the power can be transmitted.

4.3.4 Profit maximization

Total production, and then also the price level, is in the model determined by profit maximization behavior on the part of the producers as well as by the competitive environment. For a firm fc the profit is written:

$$\pi_{fc} = P_r(S_{Fr})S_{fcr}(1 - \gamma_{cr}) - C_{fc}(S_{fcr}) - \varphi_g \omega_{gcr} S_{fcr}; \quad \forall fc \text{ and } r, \quad (14)$$

subject to a non-negativity constraint on S_{fcr} , and where S_{Fr} denotes total sales by all firms in destination country r and $C_{fc}(S_{fcr})$ is the cost function for firm fc . The profit maximizing first order condition is then the following, given that firm fc is assumed to be a price taker:²³

$$\frac{\partial \pi_{fc}}{\partial S_{fcr}} = P_r(1 - \gamma_{cr}) - \frac{\partial C_{fc}}{\partial S_{fcr}} - \varphi_g \omega_{gcr} \leq 0; \quad \forall fc \text{ and } r. \quad (15)$$

It follows that, if the marginal revenue in country r is strictly lower than the marginal cost of generation and transmission, then the profit maximizing sales of firm fc in country r is equal to zero. Thus, S_{fcr} , which must be non-negative, is positive only if the expression in (15) is satisfied as an equality. Furthermore, from this follows that in equilibrium the complementarity condition below has to be satisfied:

$$S_{fcr} \left(P_r(1 - \gamma_{cr}) - \frac{\partial C_{fc}}{\partial S_{fcr}} - \varphi_g \omega_{gcr} \right) = 0; \quad \forall fc \text{ and } r. \quad (16)$$

If firm fc instead is assumed to be a price maker, the first order condition is slightly more complex. For firm fc it is written:

$$\frac{\partial \pi_{fc}}{\partial S_{fcr}} = \left(P_r + S_{fcr} \frac{\partial P_r}{\partial S_{fcr}} \right) (1 - \gamma_{cr}) - \frac{\partial C_{fc}}{\partial S_{fcr}} - \varphi_g \omega_{gcr} \leq 0; \quad \forall fc \text{ and } r, \quad (17)$$

²³ At this point the transmission losses constitute a problem since they are assumed to be constant and are always present during the profit maximization considerations. In a sense this is not a problem in itself. The caveat concerns the fact that if power flows in both directions the actual losses faced by the firms selling electricity on the foreign market are smaller than what follows from the constant loss used here. However, given the relatively small size of the constant losses used this should not have a great impact on the results other than a small difference in the equilibrium price.

given that the output decision by firm fc does not affect the output decision by any other firm. As in the previous case the following complementarity condition has to be satisfied in equilibrium:

$$S_{fc} \left(\left(P_r + S_{fc} \frac{\partial P_r}{\partial S_{fc}} \right) (1 - \gamma_{cr}) - \frac{\partial C_{fc}}{\partial S_{fc}} - \varphi_g \omega_{gcr} \right) = 0; \quad \forall fc \text{ and } r. \quad (18)$$

The model is then solved based on assumptions for two different competitive equilibria. The first competitive equilibrium is based on short run marginal cost pricing. This equilibrium is in a sense a "floor" as to how far down fierce competition possibly can push the market clearing price on the electricity market. The price is determined as the short-run marginal cost or as the price that clears the market given the existing capacities. In terms of the expressions above this corresponds to the first order condition in (15) and can be viewed as the standard perfectly competitive market price-equal-to-marginal-cost condition. In the numerical examples that follow this equilibrium will be referred to as the perfectly competitive equilibrium.

As in previous chapters the main interest is focused on market power and the level of concentration in the power industry. By assuming Cournot competition, the possible influences on market prices resulting from dominating firms that use their market power, will be evident in the analysis. Thus, the second equilibrium that is estimated is the Cournot equilibrium. As usual in a Cournot equilibrium it is assumed that each firm knows the market demand and takes the output of the other firms as given. For the estimation of this equilibrium the condition in (17) is used. It should be pointed out that the fringe firms are assumed to behave as price takers also in this case. This computed equilibrium is referred to as the Cournot equilibrium in the numerical examples.

No uncertainty exists in the model. However, on the electricity market both supply of and demand for electricity is uncertain. The primary source of uncertainty is the weather, since the supply of hydro power depends on actual precipitation and the demand for electricity in Sweden will be higher than usual during an extremely cold winter. The deterministic outcome of the model can be viewed as the solution in expectancy terms of a case where probabilities for different precipitation levels have been used. In order to account for different weather situations the model will be solved deterministically for three different levels of precipitation: a normal year, a wet year and a dry year. This can be viewed as a sensitivity analysis and enables us to study both how the level as well as the spread of market prices of electricity are affected by the meteorological conditions at hand.

This completes the description of the model. It is empirically implemented by means of production cost and capacity distribution data from the power industry, and calibrated to the actual situation in 1991. The model is solved using GAMS software (see Brooke et.al. (1988)), and a standard run takes approximately 1 minute on a Pentium PC.

4.4 The base case

Before the analysis is carried out a reference scenario is established. The model is calibrated around this base case which is intended to describe the situation in the electricity market as it was prior to deregulation. The base year is 1991 since it in the case of Sweden can be viewed as the last normal year prior to the deregulation, both from a weather perspective and from the point of view that the firms on the market had not yet started to act strategically in anticipation of the market reform. One problem exists with this base year since the Norwegian market was deregulated already in 1991 and this may have affected the data describing the market. However, since the same base year must be used for the two countries the model is calibrated to the 1991 level of electricity production, both in total and for individual firms, and to the wholesale market price of electricity.²⁴

Table 4.4 Technologies and variable costs for electricity production.

Technologies	Cost/kWh
Hydro power	1.5 Öre ²⁵
Nuclear power	7 Öre
Fossil power	9-22 Öre

Source: NUTEK(1991 and 1992), SOU 1995:140 and Nordhaus (1995)

Estimates of the variable costs associated with the different sources of power generation used in the model were discussed in Chapter 1 and are displayed in Table 4.4 as a service to the reader. The cost for hydro power production is assumed to be the same in Norway as in Sweden.

²⁴ The price formation in the model is based on one-year contracts for customers with a representative time-of-use profile for their electricity use over the year.

²⁵ 100 öre = 1 SEK = 0.13 US \$, October 3, 1997.

4.5 Price development in a deregulated Nordic electricity market

In the base case the calibrated production level of electricity for Sweden is 142.5 TWh, while the equilibrium price is 18 öre/kWh. For Norway the corresponding figures are 110.0 TWh and 17 öre/kWh, respectively. In the base case there is no electric power transmitted between Norway and Sweden. The base case serves as a norm of comparison for the goal of lower market prices and increased competition following deregulation and integration of the electricity market. In order to capture the development that follows from the integration of the Norwegian and the Swedish electricity markets, the first part of the analysis is focused on the individual markets when they are closed off for trade of electricity. In the second part the border between Norway and Sweden is then opened to allow for transmission of electricity on the existing lines.

4.5.1 Border closed for transmissions ²⁶

If an outcome with a perfectly competitive equilibrium is assumed for the wholesale electricity market, the result is indeed a lower market price in both countries. The perfectly competitive equilibrium price, with given production capacities, is 15.1 öre/kWh in Sweden and 16.0 öre/kWh in Norway, as can be seen in Table 4.5. This indicates a possibility for a price reduction after deregulation.

If the model is solved for a Cournot equilibrium instead, the result is a significantly higher price in Sweden. As can be seen in Table 4.6 the level of electricity sales in Sweden is considerably lower in the case of a Cournot equilibrium, when compared to a perfectly competitive equilibrium. The reason is mainly that production is held back by the largest firm VATT in the Cournot equilibrium. In more exact terms VATT reduces the nuclear power production from 40 TWh in the perfectly competitive case to only 14 TWh in the Cournot case, as has been pointed out in previous chapters. The price increase in Norway, with a much less concentrated market, is much smaller when compared to the perfectly competitive case. The price of 16.8 öre/kWh is even below the base case level.

²⁶ In the model a border closed for transmissions implies that $\gamma_{cr} = 1$ for all c and r .

Table 4.5 Computed equilibrium autarky prices in Sweden and Norway.

	Sweden	Norway
<u>Closed border</u>		
Perfectly competitive equilibrium (Öre/kWh)	15.1	16.0
Cournot equilibrium (Öre/kWh)	24.5	16.8

Note: The prices are excluding V.A.T. and electricity tax per kWh.

The price in the Cournot case is for Sweden approximately 1.5 times higher than the perfectly competitive price. Since the perfectly competitive equilibrium price is equal to the common marginal cost of production for all the firms, it can be considered as a lower bound for what the price can be reduced to when competition in the electricity market is fierce. The results for a Swedish market indicate that with given production capacities it is possible that the price in a deregulated market may indeed be higher than before, and that firms may achieve a high mark-up through strategic behavior. This result has also been shown in Andersson and Bergman (1995).

Table 4.6 Computed electricity sales in Sweden and Norway.

	Sweden	Norway
<u>Closed border</u>		
Perfectly competitive equilibrium (TWh)	155.6	112.6
Cournot equilibrium (TWh)	122.3	110.7

Note: All results are before losses.

As concluded previously the high degree of concentration among the Swedish power producers is a threat to the main motives behind the deregulation of the electricity market, i.e. increased competition and the downward pressure on the price level that follow from this. It remains to be seen whether the integration in the model of the Swedish and Norwegian markets will have the desired effect of decreasing the market power of the dominant firms in Sweden.

4.5.2 Border open for transmissions

The results above are based on strictly national electricity markets without possibilities to trade power across the border between Sweden and Norway. When the two markets are integrated into one single market, a market place of approximately twice the size of the national electricity markets is created. On this new market producers in both countries have the possibility to sell electricity to both domestic and foreign customers. When doing so the flow of power across the lines, and particularly the capacity limitations of the power lines at the border between Norway and Sweden, may become an important part of the price formation and competition in the electricity market.

To open the border for transmission, and thus integrate the Norwegian and Swedish electricity markets, has an impact on the outcome of the equilibrium prices, as can be seen in Table 4.7. The equilibrium prices are almost equalized in both countries, both for the perfectly competitive equilibrium as well as the Cournot equilibrium. For the perfectly competitive equilibrium the changes that follow the opening up of the border are rather small: the Norwegian price has decreased a little bit and the Swedish price is somewhat higher. The real interesting part is the outcome for the Cournot equilibrium: the Norwegian price is a little bit higher than before but the Swedish price has dropped by more than 7 öre/kWh, which is a dramatic change from the situation with the closed border.

Table 4.7 Computed equilibrium free trade prices in Sweden and Norway.

	Sweden	Norway
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (Öre/kWh)	15.3	15.9
Cournot equilibrium (Öre/kWh)	17.4	17.1

Note: The prices are excluding V.A.T. and electricity tax per kWh.

The amount of electricity sold in Sweden after the integration of the markets is even higher under the assumption of Cournot competition than for the base case. The Cournot equilibrium sales in Sweden are equal to 144.9 TWh, as can be seen in Table 4.8, and sales in Sweden was

equal to 142.5 TWh in the base case. As a result of the larger sales volume in Sweden the Cournot equilibrium price is also lower than the corresponding base case price.

Table 4.8 Computed electricity sales in Sweden and Norway.

	Sweden	Norway
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (TWh)	155.4	113.7
Cournot equilibrium (TWh)	144.9	109.8

Note: All results are before losses.

The question is then what the forces are on the integrated electricity markets that have this effect on the equilibrium price. In Table 4.9 the equilibrium electricity sales in one country by firms from the other country are displayed. In the case of the perfectly competitive equilibrium there are no sales in Sweden by Norwegian firms and 0.1 TWh are sold in Norway by Swedish firms. These sales obviously result in a net transmission of 0.1 TWh of electricity from Sweden to Norway, which also is shown in Table 4.10 below.

For the Cournot case the sales by foreign firms are much larger. As displayed in Table 4.9 Norwegian firms sell as much as 53.8 TWh in Sweden in equilibrium. The corresponding volume of 53.1 TWh of sales in Norway by Swedish firms means that, although the turnover of foreign sales is large there is only a net flow of 0.7 TWh going from Norway to Sweden. These results indicate an important aspect of the electricity market, namely that there is a significant difference between the 'contractual flows' of electricity and the actual physical flows.

The behavior by the firms and the dramatic fall in the Swedish Cournot equilibrium price level on the integrated electricity market, can be understood as an example of reciprocal dumping (see for example Brander and Krugman (1983)). The firms in both countries would like to maintain a high price level on their domestic markets and may therefore be inclined to cut back on production and sales in order accomplish this. However, since they have a market in the other country where the held back production can be sold at the market price they may prefer to run their plants and sell abroad. Since all firms in both countries have a motive to sell at the market price in the foreign market and to maintain a high domestic price the end

result may very well be as in this case with almost no difference in prices between the markets, even in the case of Cournot competition.

Table 4.9 Computed electricity sales in one country by firms from the other country.

	In Sweden (By Norwegian firms)	In Norway (By Swedish firms)
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (TWh)	0.0	0.1
Cournot equilibrium (TWh)	53.8	53.1

Since almost all the trade is taking place as "contractual flows" and the net transmissions are very small, the resulting transmission losses and the associated costs remain quite small. The question of unnecessary transports is otherwise an issue in the cases of reciprocal dumping, something that seems to be avoided here given the nature of the Nordic electricity market. Actually the small net flow that has been computed indicates that there is really no need for a large transmission capacity between Norway and Sweden in order to achieve a competitive integrated electricity market. All that is needed is a transmission line creating the possibility to sell electric power on the foreign market. When all contracts then are closed, with a large turnover in traded electricity as a result, the net transmissions across the border turn out to be quite small.

Table 4.10 Computed net transmissions of electric power across the border.

	To Sweden	To Norway
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (TWh)	-0.1	0.1
Cournot equilibrium (TWh)	0.7	-0.7

As a comparison to this integrated Swedish and Norwegian market a scenario is constructed which consists of a doubling of the Swedish market, i.e. two Swedish markets joined together.

On this new market there are two firms such as VATT and two firms equal to SYD and so on. The computed equilibrium price is in this case equal to 17.5 öre/kWh in both 'countries'. The resulting net transmission of electric power is non-existent, but the gross turnover is quite large. Thus, at the outset there are two equal countries where the dominant firms have a possibility to maintain a high mark-up. Then, when the possibility to trade across the border materializes this creates a situation with increased competitive pressure, which in turn has a considerable effect on the equilibrium prices.

The outcome with a large trade and small net transmission is an equilibrium result and it is not possible to follow the path from no trade to full trade in the model. Even though the restriction on the transmission lines of 5 TWh does not bind in equilibrium it is not possible to rule out that this may occur during a transitional phase when the firms start up their sales on the foreign markets.

4.6 Sensitivity analysis: Supply of hydro power

4.6.1 Border closed for transmissions

As has been discussed earlier the supply of hydro power is uncertain and can vary significantly between years. The varying precipitation leads to different production possibilities for the firms with hydro capacity in their portfolio of production units. At a given level of production this shift implies an increase or a decrease in the marginal costs for the firms in a dry year or a wet year, respectively. Naturally the Norwegian firms are more sensitive to variations in precipitation since they rely entirely on hydro power in their production system. In order to study how both the level and the spread of the electricity market price is affected by the meteorological conditions, under different assumptions concerning the competitive environment, two additional types of scenarios are included. Thus, scenarios consisting of a dry year with 25 % less precipitation and a wet year with 25 % more precipitation than a normal year are computed.²⁷

In general variations in precipitation means a lower electricity market price a year when the supply of hydro power is large and a higher price than for the normal year when the

²⁷ It is assumed that precipitation in Norway and Sweden is positively correlated, i.e. a wet year in Norway coincides with a wet year in Sweden and similarly for dry years. This is true for most periods, although it may not be correct in the sense that precipitation between the two countries is perfectly correlated.

precipitation is small. This is also the case for both the perfectly competitive equilibrium and the Cournot equilibrium, as can be seen in Table 4.11.

Table 4.11 Computed equilibrium autarky prices on the electricity market for periods with different precipitation.

	Sweden	Norway
<u>Closed border</u>		
Perfectly competitive equilibrium (Öre/kWh)		
Dry year (- 25% Hydro power)	16.6	26.6
Wet year (+ 25% Hydro power)	14.3	10.8
Cournot equilibrium (Öre/kWh)		
Dry year (- 25% Hydro power)	26.5	28.3
Wet year (+ 25% Hydro power)	21.3	10.9

Note: The prices are excluding V.A.T. and electricity tax per kWh.

The greater sensitivity for variations in precipitation built into the Norwegian electricity market results in a wider span between the lowest and the highest equilibria prices. Obviously this is the case for both the perfectly competitive equilibrium as well as the Cournot equilibrium. It is vital to keep in mind that no transmissions of electric power are allowed in these scenarios.

4.6.2 Border open for transmissions

From the earlier results it has been shown that the net flow of power across the border between Sweden and Norway are quite small during a normal year. One question is then whether the restriction on the transmission lines between the two countries will become a binding restriction when the supply of hydro power varies between more extreme levels. This is especially an interesting issue given the difference between the power industries in the two countries, with Norway relying entirely on hydro power and Sweden with a mix of hydro and nuclear power.

For the perfectly competitive equilibrium it is not possible to transmit enough power over the lines during a dry year, in order to have a significant equalization of the price level in both

countries, as can be seen in Table 4.12. Although the price in Norway is lower than when the border was closed, the limit of 5 TWh is obviously not high enough to allow a large enough flow during the period. For the wet year the transmission lines almost suffice for the perfectly competitive equilibrium, since the computed equilibrium prices observed in Norway and Sweden are much closer together.

Table 4.12 Computed equilibrium prices in Sweden and Norway for periods with different precipitation.

	Sweden	Norway
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (Öre/kWh)		
Dry year (- 25% Hydro power)	16.9	24.9
Wet year (+ 25% Hydro power)	12.9	11.4
Cournot equilibrium (Öre/kWh)		
Dry year (- 25% Hydro power)	21.5	25.9
Wet year (+ 25% Hydro power)	16.9	12.2

Note: The prices are excluding V.A.T. and electricity tax per kWh.

Under the assumption of Cournot competition the extreme precipitation levels have a clear impact on the computed equilibrium prices, both regarding the levels and the spread. During a normal year the strategy to sell power at the market price in the foreign market, while trying to maintain a high price level on the domestic market, resulted in a large turnover in electricity trade, but a very low level of net transmissions. In addition this strategy of reciprocal dumping resulted in almost the same low equilibrium price level in both countries. When the precipitation level is different from normal this affects a hydro dependent power production system, like the Norwegian, relatively more than the mixed system in Sweden. This in combination with the reciprocal dumping strategy from the firms in both countries have the effect that the large volume in 'contractual electricity flow' results in a high level of physical flows, which in turn makes the capacity of the transmission lines insufficient. Thus, with a binding transmission restriction the price levels established in equilibrium in each country converge, but remain relatively far apart.

Depending on whether it is a dry or a wet year the country with the highest price level is different. This has to do with the relative dominance of hydro power in the respective countries: during a wet year the production possibilities are increased relatively more in Norway than in Sweden, and during a dry year the Swedish producers maintain more of their regular production capacity than the Norwegian producers do. That the flow of power goes in different directions can also be seen in Table 4.13. From those figures it is clear that the transmission line is fully utilized in both a dry and a wet year.

Table 4.13 Computed net transmissions of electric power across the border for periods with different precipitation

	To Sweden	To Norway
Open border (Maximum 5 TWh)		
Perfectly competitive equilibrium (TWh)		
Dry year (- 25% Hydro power)	-5.0	5.0
Wet year (+ 25% Hydro power)	5.0	-5.0
Cournot equilibrium (TWh)		
Dry year (- 25% Hydro power)	-5.0	5.0
Wet year (+ 25% Hydro power)	5.0	-5.0

As for a normal year there is a large volume sold on the foreign market by the firms in both the dry and wet year when Cournot competition is assumed. Thus, under Cournot competition there is a large 'contractual flow' of electric power between the countries regardless of the amount of precipitation.

4.7 Concluding remarks

The main motive behind the deregulation of the electricity market has been to increase competition and to achieve lower market prices. As pointed out before, which has also been shown in Andersson and Bergman (1995), with the given structure of the power producing firms in a Swedish electricity market, a deregulation is not a sufficient condition for lower equilibrium prices.

However, in a market where the Swedish electricity market is integrated with the Norwegian electricity market, the outcome is a dilution of the market power realized by the dominant firms. In the present analysis, with the restrictions on the transmission lines between Norway and Sweden modeled explicitly, it is clearly the case that the integrated market creates a situation where the competitive environment puts a strong downward pressure on the price of electricity. In equilibrium during a normal year there is a large volume of 'contractual flows' of electricity across the border, but only a small amount of physical net flow of electricity. However, for more extreme years when precipitation is well above or below the normal level the result alters. Then the physical flows become large enough to create bottle necks on the border between Norway and Sweden. As a result, different price regions are established in the two countries.

In conclusion this numerical exercise has shown that the integrated and expanded Nordic electricity market is vital in creating a well functioning competitive environment for the different actors. It is furthermore clear that the transmission lines and the existing bottle-necks play an important role in this. This is particularly the case during periods with extreme levels of precipitation.

Appendix 4.A - Parameter values

Price elasticity

$$\eta_c = -0.5 ; \quad \forall c.$$

Transmission losses

$$\gamma_{cr} = 3 \% ; \quad \forall c \text{ and } r.$$

Capacity on the transmission line between Norway and Sweden

$$TMAX_g = 5 \text{ TWh}$$

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Part 2

A phaseout of Swedish nuclear power

Chapter 5

Power Production and the Price of Electricity: An Analysis of a Phaseout of Swedish Nuclear Power *

5.1 Introduction

In Sweden energy policy in general and the electricity market in particular has been in the focus of attention for some time. The main reason being a referendum held in 1980 concerning the future of Swedish nuclear power. Following the referendum the Swedish parliament decided that no further nuclear reactors would be licensed and that the existing nuclear reactors should not be permitted to operate beyond the expected lifetime of the latest reactor installed. A year that was explicitly pointed out was 2010. To complicate matters further there are three additional decisions taken by the Swedish parliament that in fact are closely related to the issue of phasing out the nuclear power.

First, concerns about global warming, the greenhouse effect, have brought the parliament to commit Sweden not to increase CO₂ (carbon dioxide) emissions above 1990 levels. If nuclear power is phased out, it would probably be economical to replace some of the electricity production by fossil-fuel-powered electricity. But this would lead to higher CO₂ emissions, which would threaten the CO₂ commitment.

* This chapter was co-authored with Erik Håden. The basic modeling work was made in connection with a report on Swedish energy policy by William D. Nordhaus (see Nordhaus (1995)).

Secondly, the parliament has decided that the rivers and river stretches that are unharnessed, i.e. excluded from hydro power development, will remain protected in the future. Obviously this excludes hydro power, which today makes up for about half the Swedish electricity production, as a large-scale substitute for nuclear power.

Thirdly, in 1991 an agreement by a majority of the parliament added one very broad, yet critical, policy objective. It stated that one major purpose of energy policy in Sweden was to secure the short-term and long-term supply of electricity on internationally competitive terms. In the agreement the parties emphasized that secure supplies of electricity, reasonably priced, were an important condition for the international competitive strength of Swedish industry. If the nuclear power is to be phased out and the possibility to replace it by the relatively inexpensive techniques of fossil fuel power and hydro power are excluded as a result of the CO₂ commitment, the price and supply of electricity will most certainly be affected.

All in all the politicians have decided on a set of conditions for the energy sector, which together are impossible to fulfill. Even if the condition of inexpensive electricity to the industry is disregarded the other conditions might prove to be expensive to society in terms of direct costs and industry restructuring.

The purpose of this paper is to study the effects of different policy scenarios with respect to Swedish energy policy, specifically issues concerning a nuclear phaseout and restrictions on CO₂ emissions. This is done by the means of a dynamic partial equilibrium model of the Swedish energy market where the interdependence between the electricity market and the markets for heating is modeled explicitly. As a basis for our scenarios we use the restrictions on future energy policy imposed by the Swedish parliament.

Swedish energy policy has been studied thoroughly on several occasions. The latest example is a study by Nordhaus (1995) where he focuses on the effects of a nuclear phaseout and the related CO₂ commitment issue. The major difference between our approach and the one in Nordhaus' study is that his is more macro-oriented. The model we use is more disaggregated and focus on the electricity market in detail and is intended to capture the important interrelation between the heat markets and the electricity market. The issue of a Swedish nuclear phaseout has also been studied by Amundsen et. al. (1994)²⁸. They use a static multi country model where the production facilities in different countries and the transmission possibilities between different national electricity grids are taken into account when the

²⁸ The report in the reference list contains a description of the model in question. The study of a Swedish nuclear phaseout is in Norwegian. A complete reference to this study can be obtained at request.

effects of a phaseout of Swedish nuclear power is discussed. The model we use allows for imports of electricity, although this is modeled in a less sophisticated way than in Amundsen et. al.. Instead of focusing on the international dimension, as in their study, our model focuses on an inter temporal dimension and the electricity market's development over time following a Swedish nuclear phaseout.

The remainder of the chapter is structured as follows. The next section gives a brief description of the Swedish electricity and heat markets. In section 5.3 the model is presented. This is followed by a section where a Base Case is introduced. In section 5.5 different policy scenarios are described and analyzed. Section 5.6 contains a sensitivity analysis. Some concluding remarks are then made in the final section.

5.2 The Swedish electricity and heat markets

An interesting feature of the present electricity production in Sweden is that hydro and nuclear power together account for more than 95 % of total power production, and that the annual nuclear production is approximately equal to the annual hydro production. The remaining production comes from plants fired by either coal, oil, natural gas or biomass. On the demand side one can observe that more than 20 % of the electricity is used for heating purposes. The electricity used for heating is equally divided between direct electric heating and waterborne heating.

In the case of district heat production the plants are either cogeneration plants, heat plants (ordinary combustion), heat pumps, electric boilers or industrial backpressure. It should be pointed out that this sector may produce large amounts of electricity from the cogeneration plants when this is profitable, i.e. when electricity prices are high relative to the alternatives. When electricity prices are low this sector may instead, at short notice, swing over to become a large net consumer of electricity by using for example electric boilers to produce heat. The supply of district heating is restricted to certain geographically limited regions.

5.3 The model

Our model, DELMARK, is a dynamic partial equilibrium model. It originates from a static model, ELMARK, documented in Carlsson (1988). In DELMARK six energy markets in

Sweden are explicitly treated: One nation-wide electricity market, three regional markets for district heating, and one market each for light oil and heavy oil, respectively. Through the model, equilibrium prices and quantities can be obtained for each of the markets. In comparison to energy models such as MARKAL (see for example Fishbone and Abilock (1981)) and MESSAGE (see for example Messner (1984)), it is important to point out that DELMARK is a *market model* focusing on equilibrium prices and volumes of commercially traded energy such as electricity, and not an *energy system model* designed to find an optimal plan to meet an exogenous demand for useful energy.

The design of the model is intended to capture some "stylized facts" about the Swedish electricity and district heating markets. Thus, the model is specifically designed to capture the essentials of an interdependent system of, on one hand, production and use of electricity and, on the other hand, production of and demand for heat. The complex interdependence between the national electricity market and the different regional markets for heating is present both on the supply and the demand side. As mentioned above, production of electricity in combined heat and power plants may require a certain demand for district heating in order to be economical. Furthermore, district heating can be produced by large electric boilers. In addition to that, individual heating systems based on electricity are possible substitutes for district heating. The actual market share of district heating, which is set exogenously, has been determined by the existence of local and regional distribution networks for district heating as well as by the costs associated with the use of other energy carriers in individual heating systems.

From these facts follows that the description of the demand for energy for heating purposes, including different substitution possibilities, is a central part of the model. The foundation of this in the model is the way the country has been divided into different markets for district heating. These regional markets are labeled "Heat Markets".

The first heat market includes areas where large integrated district heating systems exist or are under construction. Thus, "Heat Market 1" is the potential market for large scale (200 MW or more) combined heat and power or combustion plants.

On "Heat Market 2" only small scale district heating plants exist and another special characteristic of "Heat Market 2" is that it consists of areas which are situated where the supply of domestic fuels, such as biomass, is large. In these areas district heating is or will be an alternative way of heating in the future.

"Heat Market 3" consists of the remaining district heating areas in Sweden where no supply of domestic fuels exist. The major difference between this market and "Heat Market 1" is that no large scale district heating plants are assumed to exist on "Heat Market 3".

This separation into different heat markets is made in order to capture the relationship between the alternatives of production and the total demand for heating on a local market for district heating.

For the remaining areas of the country, there exist no district heating today or any plans to construct such plants in the future. In order to complete the picture, a market for light oil and a market for heavy oil are treated alongside with the model. The market for light oil is based on the demand for heat in the housing sector and the market for heavy oil consists mainly of industrial demand. Oil is assumed to be used for combustion in the industry. Both the light and the heavy oil are assumed to be imported at given world market prices. The volumes of the two markets are accounted for in order to capture the total emissions from the Swedish energy sector. The general structure of the model is outlined in Figure 5.1. The different generation sources and their associated costs are described in Appendix 5.A.

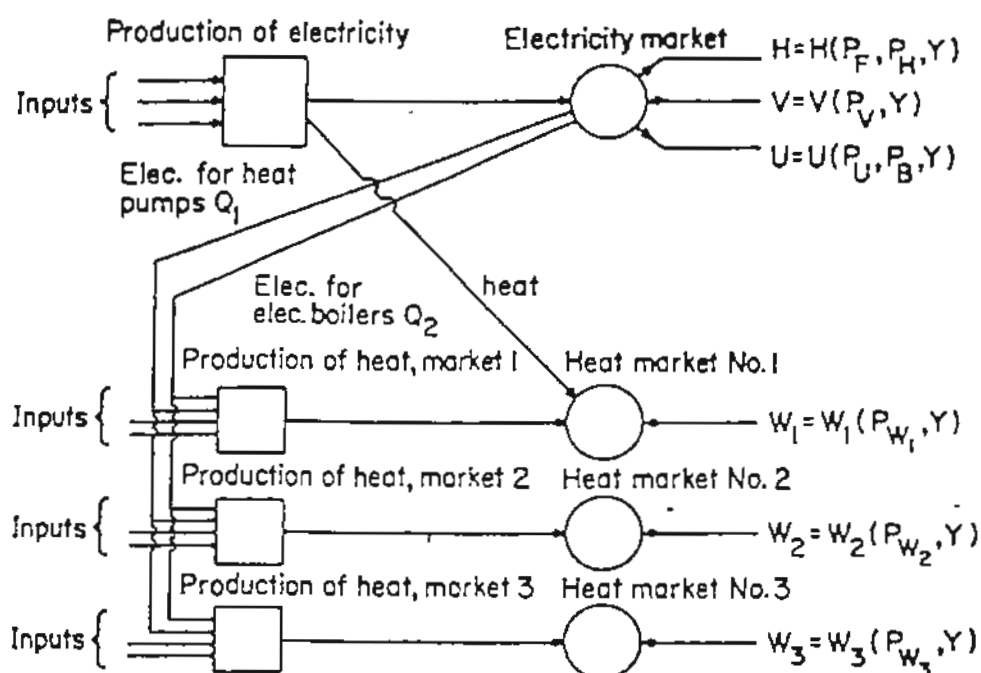


Figure 5.1 General structure of the model.

The demand for electricity

- for waterborne heating:
- for direct electric heating:
- for all other uses:²⁹

$$H = H(P_H, P_F, Y)$$

$$V = V(P_V, Y)$$

$$U = U(P_U, P_B, Y)$$

The demand for heat on Market 1:

$$W_1 = W_1(P_{W1}, Y)$$

The demand for heat on Market 2:

$$W_2 = W_2(P_{W2}, Y)$$

The demand for heat on Market 3:

$$W_3 = W_3(P_{W3}, Y)$$

The price of light oil (exogenous):

$$P_F$$

The price of electricity

- for waterborne heating:
- for direct electric heating:
- for all other uses:

$$P_H$$

$$P_V$$

$$P_U$$

The price of heavy oil (exogenous):

$$P_B$$

The price of heat on Market 1-3:

$$P_{W1}, P_{W2} \text{ and } P_{W3}$$

Real income:

$$Y$$

²⁹ This category consists of electricity used in industry, transportation, and in households for non-heating purposes.

Several of the demand relationships above are of a short-term nature although the model is used in a long-term setting. The short-term nature is partly motivated by the fact that substitution possibilities that exist in the energy sector are often influenced by the political process, and are thus virtually impossible to foresee in the distant future. Given this it seems reasonable to limit the substitution possibilities. Furthermore, an expansion of district heating is very much dependent upon geographical conditions. This together with the political influence on the energy sector motivates that the mixture and growth of the heating systems are exogenously determined in the model. In addition, the fact that future location and size of district heating systems are determined by spatial conditions, such as migration patterns, which today are hard to predict, makes it difficult to endogenously determine the size of the heating systems.

The numerical values of the different elasticities for the demand equations, as well as other relevant parameter values, are displayed in Appendix 5.B. Since the demand functions in the model are linearisations of nonlinear functions, the elasticities are only exactly right in the area close to the calibrated equilibrium.

Perfect competition is assumed throughout this paper for reasons of simplicity. However, the Swedish electricity market is characterized by a high degree of concentration, with the largest firm, state owned Vattenfall, accounting for more than 50 % of total production and the ten largest producers together making up for more than 95 % of total power production. This circumstance may be important for production levels and market prices. See Andersson and Bergman (1995) for a discussion of competition and prices on the Swedish electricity market.

In energy models it is important to account for the fact that a year consists of both peak and off-peak periods of electricity demand. In this model time is divided into three different load periods. Furthermore, the production of hydro power is only restricted by the maximum annual energy production and maximum capacity. This implies that hydro power production freely can be redistributed between the different load periods, as long as it does not exceed these limits.³⁰

The electricity production is equal to the sum of utilized capacity in different plants times the number of hours they have been in use. For total supply of electricity production to equal

³⁰ In order for this to be correct we have to assume that free hydro power storage capacity exists over the year, which of course is not literally true, but a close enough approximation for our model.

demand on the electricity market the following condition has to be met:

$$\begin{aligned}
& (1-\sigma_e) \sum_f \sum_a K_{efa}^\tau T^\tau + (1-\sigma_e) \sum_f \sum_a \sum_w K_{efaw}^\tau T^\tau + (1-\sigma_e) IMP_t^\tau \\
& = V_t^\tau + H_t^\tau + U_t^\tau + HP_t^\tau + EB_t^\tau, \quad \text{for } \tau = 1,2,3 \text{ and } t = 1,2,\dots,9
\end{aligned} \tag{1}$$

where σ represents distribution losses, K is utilized capacity and T is number of production hours. Generation can be either from plants producing only electricity, denoted by subscript e , or from plants where electricity is cogenerated with heat, denoted by subscript c . The capacity K_c represents the electrical power capacity in a combined heat and power plant (CHP). The CHPs are located in different heat markets, denoted by w . The subscripts f and a refer to different fuels and abatement technologies, respectively. The subscript t indicates that the equality has to hold for each time period t . The load periods are denoted by superscript τ . IMP represents total imports of electricity before losses. Regarding the trade of electricity it is assumed that electricity can be bought at a "world market price". If it is competitive, electricity will be imported and supplied to the national market. There is a restriction on imports due to limited transmission capacity. At all given levels of output the utilization of the different types of plants is determined by cost minimization considerations.

On the demand side, V represents the electricity demanded for direct electric heating, H is electricity demanded for waterborne heating, and U is electricity demanded for other uses, primarily industry. HP is electricity demanded for heat pumps and EB is electricity demanded for electric boilers. All the demand for electricity is at the user.

For the three heat markets the corresponding market clearing conditions can be written:

$$\begin{aligned}
& (1-\sigma_h) \sum_f \sum_a \gamma K_{cfa1}^\tau T^\tau + (1-\sigma_h) \sum_f \sum_a K_{hfa1}^\tau T^\tau = W1_t^\tau, \\
& \text{for } \tau = 1,2,3 \text{ and } t = 1,2,\dots,9
\end{aligned} \tag{2a}$$

$$\begin{aligned}
& (1-\sigma_h) \sum_f \sum_a \gamma K_{cfa2}^\tau T^\tau + (1-\sigma_h) \sum_f \sum_a K_{hfa2}^\tau T^\tau = W2_t^\tau, \\
& \text{for } \tau = 1,2,3 \text{ and } t = 1,2,\dots,9
\end{aligned} \tag{2b}$$

$$(1 - \sigma_h) \sum_f \sum_a \gamma K_{efa3t}^\tau T^\tau + (1 - \sigma_h) \sum_f \sum_a K_{hfa3t}^\tau T^\tau = W3_t^\tau, \quad (2c)$$

for $\tau = 1, 2, 3$ and $t = 1, 2, \dots, 9$

where total heat production has to be equal to total demand for each time period t and for each load period τ . Plants of cogeneration type, K_c , produce γ units of heat for each unit of electricity. Plants producing only heat are represented by K_h . The $W1$, $W2$, and $W3$ represent the demand for heat, at the user, on the different heat markets.

At a given point in time total output is constrained by the installed capacities \bar{K}_e , \bar{K}_c and \bar{K}_h . For electricity production this can be written:

\bar{K}_{efa1} exogenously given,

$$\bar{K}_{efat} = (1 - \delta) \bar{K}_{efat-1} + I_{efat-1}, \quad \text{for } t = 2, 3, \dots, 9 \text{ and } \forall f \text{ and } a \quad (3)$$

and

$$K_{efat}^\tau \leq \alpha_{efa} \bar{K}_{efat} \quad \text{for } \tau = 1, 2, 3, t = 1, 2, \dots, 9 \text{ and } \forall f \text{ and } a \quad (4)$$

where \bar{K}_{efat} is total installed electricity production capacity at time t for each combination of fuel and abatement, respectively. The superscript τ is dropped for *installed* capacity since it is the same over the different load periods during each time period t . The δ is the depreciation rate of the production units. I_{efat} is equal to investments in plants of type efa made at time t . From equation (3) it is clear that an investment made at $t-1$ will not become available for production until time t . The intention of this is to capture the lag between the investment decision and the availability of the plant associated with investments in large power production units. The condition in equation (4) states that total capacity utilized, K_{efat}^τ , have to be less than or equal to the accessibility, α_{efa} , times installed capacity, \bar{K}_{efat} , at each time t and load period τ . Corresponding conditions exist for plants of type c and h as well.

The total investment cost is taken in the time period when the investment is made. The issue of remaining terminal values of the installed capacity at the end of the time horizon is important to take into account. This issue is dealt with by decreasing the investment cost over time according to an annuity calculation. Thus, the fact that investments made late in the model's time horizon actually have an economic life beyond the model's time-span is compensated for by a lower investment cost.

There is an equation adding the CO₂ emissions from the different sources of electric power and heat production. This equation can be written as:

$$EMI_t = \sum_{\tau} \sum_f \sum_a \theta_{efa} K_{efa\tau}^{\tau} T^{\tau} + \sum_{\tau} \sum_f \sum_a \sum_w \theta_{cfa} (1 + \gamma_{fa}) K_{cfa\tau}^{\tau} T^{\tau} + \sum_{\tau} \sum_f \sum_a \sum_w \theta_{hfa} K_{hfa\tau}^{\tau} T^{\tau},$$

for $t = 1, 2, \dots, 9$ (5)

where EMI is total emissions and θ is the emission coefficient associated with the different types of production, fuels, and abatement technologies.

Total CO₂ emissions can be constrained by an exogenously set limit. In such cases, the relationship can be written as:

$$EMI_t \leq \hat{EMI}_t \quad \text{for } t = 1, 2, \dots, 9 \quad (6)$$

where \hat{EMI}_t is the exogenously set limit.

The model is solved by quadratic programming and the objective function that is maximized is the discounted value of the sum of the consumers' and the producers' surpluses of the different time periods. The method of solving is similar to the one used by Manne (1974). The objective function is constructed in such a way that it measures the area under the demand curve, minus the area under the supply curve. Since the demand and supply curves, in each market respectively, contain all information about costs and preferences in the model, so will the objective function. All in all, this process implies that price has to be equal to marginal cost.³¹ For the electricity market this can be written:

$$P_{eit} = MC_{eit} \quad \text{for } t = 1, 2, \dots, 9 \text{ and } \forall i \quad (7)$$

where P_{eit} is the electricity price in demand category i at time t . MC_{eit} is the marginal cost of electricity production in demand category i at time t . Separate prices are being established in each demand category due to differences in distribution losses to different end users. Another effect of this optimization process is that no investments are made unless the present value is positive.

³¹ The marginal cost, MC , can be stated as $MC = VC + \lambda$ where VC is the variable cost and λ is a scarcity rent. The variable costs are described in Appendix 5.A.

The model, which in total consists of 42 endogenous variables and 103 equations and inequalities, is run on the GAMS software package. On a Pentium PC, a standard run takes approximately 35 minutes to solve.

5.4 The base case

Since the purpose of this paper is to estimate impacts of different policies, a natural starting point for further comparisons is a base case, defined as "business as usual". This implies that nuclear power production is assumed to continue at the current levels and no restrictions are enforced on the emissions of CO₂. Regarding capacity expansion it is assumed that no additional hydro or nuclear power is allowed at all, and new capacity from other sources can not be taken into operation until after the turn of the century due to the lead times in the decision and construction process.³² The exception is biomass - in the model consisting mainly of wooden chips and peat - which is allowed to expand shortly before the year 2000.³³ The reason for this is the existence of large state funded promotions of renewable energy sources for energy production. However, an upper limit of annual production of 10 TWh has been set for these plants in the model.

This limit may seem low since the potential for biomass often is claimed to be larger than 10 TWh in the public debate. The restriction is based on the circumstance that only about 10 TWh of electricity is possible to produce annually from biomass at the costs referred to in Appendix 5.A. The crucial assumption is that when more biomass is to be used the costs increase dramatically due to longer transportation distances. See also Nordhaus (1995) for a discussion about these issues. The biomass restriction is one of the potentially critical assumptions that are altered in the sensitivity analysis in a subsequent section. This is done in order to get a picture of how important the availability of biomass at a relatively low cost is to the results.

Another restriction concerns the possibility to import electricity to Sweden. Here the exogenous limit is set to annual imports of 10 TWh. The price paid for imported electricity is assumed to equal the cost of additional power production in a neighboring country, plus the cost of transmission losses. The reason for assuming a price equal to the cost of new power is that foreign producers would require this as payment for supplying electricity on a long run

³² The exact year is 2004 for new capacity to become available. This year is the first in the period after year 2000 in the model.

³³ Electricity from biomass can be produced by up to 1 TWh/year in 1991 and by 2 TWh/year in 1996.

basis to the Swedish market. In the short run they may be willing to sell temporary surplus power at a lower price, but in the long run for large and steady quantities additional capacity will have to be added. Since new capacity at competitive price levels is likely to be based on fossil fuels an extended import of electric power would in a broad sense imply a violation of the condition restricting Swedish CO₂ emissions, even though the emissions originate from another country. Hence follows the restriction of 10 TWh of imported electricity.

The year 1991 has been chosen as the base year for the calibration of the model. The reason being that 1991 was the latest "normal" year in terms of electricity production and to which we have access to data. Thus, the model has been calibrated to the 1991 level of electricity and heat production, both in total and for different types of production categories.³⁴ This is also the case for the market price of electricity which has been used to calibrate the price level on the different markets described in the previous section.

The time horizon in the model extends from 1991 through the year 2031. For computational reasons it is convenient to employ five-year time intervals where the year referred to is the representative midpoint year, i.e. 1991 is the representative year for the five-year interval 1989-93. Another implication of this is that all years during one five-year period are assumed to be equal, meaning that no specific conclusions can be made regarding, for example, how 1990 differs from 1992.

An ever intriguing issue in Swedish energy policy concerns the way energy taxes are designed. Since the tax level can make the difference whether a plant is competitive or not, it is vital to replicate the tax system as accurately as possible in the design of the model. Since the taxes in Sweden in general, and the energy taxes in particular, are changed every now and then it is difficult to know what they will be in the future. For our dynamic model we have included the latest major revision of the energy tax scheme, which was carried out 1993 - 1994. Fuels are to a large extent taxed according to their CO₂ emissions after this revision. An explicit emission tax was in fact introduced already in 1991, which with few exceptions replaced old taxes based on different technologies and fuels. In 1993 this emission tax was revised in order to reduce the tax burden on energy-intensive industry. After this revision the industry only pays 25 % of the nominal CO₂ tax. Fossil fuels became relatively more expensive to use as a consequence of all these changes. However, this effect should not be exaggerated since previous tax regimes to some extent implicitly taxed CO₂ emissions. For

³⁴ In order for this to be correct, all costs in the model have to be in 1991 SEK. Since the cost data originally was in 1995 SEK we had to transform them to 1991 SEK. We have assumed that the costs in 1991 were the same as in 1995 in real terms, i.e. the 1995 costs have been adjusted by the inflation in order to obtain the 1991 costs for the model.

the first period the "old" tax regime is used. This regime includes the changes of 1991 but not the revisions of 1993. From period two the "new" system of energy taxes is implemented in the model. Even though this tax scheme is likely to change over the years, we use this "new" setting for the remainder of the time horizon in the model since this is our best guess for future energy taxes. One special feature of the energy taxes is that fuels are taxed differently depending on whether they are used for electricity production or other purposes. This fact creates certain modeling difficulties regarding plants that produce a combination of electricity and heat.

A discount rate of 5 % is used throughout the model. This level is chosen mainly for the reason that it is perceived to capture the agents time preference reasonably well, but also for comparative reasons since 5 % appears to be the discount rate that is used in most other studies on this subject.³⁵ See for example NUTEK (1994).

The driving force of the model is the growth rate of the economy. An annual real growth rate of income of 2 % is assumed over the time horizon of the model. This growth rate is also used in NUTEK (1994) and Nordhaus (1995). The growth of the demand in the different markets is determined by the income elasticities, which are assumed to be 0.7 for all user groups. The exception is direct electric heating which is assumed to have an income elasticity equal to 0.³⁶

In Table 5.1 the estimated levels and growth of the main variables in the base case run are shown. From these estimates it can be seen that electricity prices will rise modestly over time. Since no additions are allowed in nuclear or hydro power production, the increased demand for electricity is at first met through production increases in existing plants that are cost-effective. Additions in electricity production from new biomass plants are made until the exogenous limit of 10 TWh at the user is reached. As demand grows further, new natural gas-fired plants are taken into operation. The use of these plants increase dramatically in this run when the emissions of CO₂ are unrestricted. The implicit CO₂ tax indicates what tax would be needed, in each year respectively, in order to keep the emissions at the prevailing level. Since CO₂ emissions are unrestricted in the base case, the implicit CO₂ tax is zero for all years. The value of the objective function is normalized to zero since it will be used for comparisons in the subsequent sections. All generation figures in this table and in the following scenarios are at the user.

³⁵ Of course the level of the discount rate can be discussed at length. In order to check for robustness of the results regarding the discount rate we carry out a sensitivity analysis with different levels of the discount rate.

³⁶ The elasticities chosen are well in line with projections made in the industry when improvements in energy efficiency have been accounted for.

Table 5.1 Summary of base case run.

	1991	2000	2010	2020
Electricity price (industry) (1995 SEK/kWh) ³⁷	0.21	0.26	0.27	0.27
Electricity use (TWh)	132	141	160	188
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	65.2	65.2	65.2
Natural gas	0.0	1.5	13.3	40.7
Fossil fuels	8.1	12.8	12.8	13.1
Biomass	0.1	2.7	10.0	10.0
Imports	0.0	0.0	0.0	0.0
Emissions				
CO ₂ (Million tons)	31	42	61	79
Implicit CO ₂ tax (1995 SEK/kg CO ₂)	0.0	0.0	0.0	0.0
Marginal generation source	Biomass	Biomass	Natural gas	Natural gas
Present value of objective function (Billions of 1995 SEK)	0			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.

Note: Fossil fuels is an aggregate of oil and coal.

Note: Biomass is an aggregate of wooden chips and peat.

Note: Present value of the objective function has been normalized to zero.

³⁷ 1 SEK = 0.13 US \$, October 3, 1997.

5.5 Different policy scenarios

5.5.1 Scenario 1 - Phaseout of nuclear power

The first policy scenario concerns the impact of fulfilling the commitment to phase out nuclear power. We do not allow any expansion of hydro power in this scenario, or in any other scenario, since it is our strong belief that expansion of hydroelectric power has almost no political support in Sweden. We do not put any restrictions on the carbon dioxide emissions. There are mainly three reasons for that: First, the wisdom of the commitment not to increase CO₂ emissions above 1990 levels is strongly debated. Secondly, the parliament of Sweden has stated that the carbon dioxide target probably will be hard to achieve. And, thirdly, we want to be able to analyze the effects of a nuclear phaseout, “other things being equal”, implying that the only change made in this scenario has to do with the installed nuclear capacity.

This scenario corresponds to the literal date pictured in the referendum, meaning a total phaseout of nuclear power in the year 2010. Since our model has five-year periods and one time period will start by the year 2009, this scenario will impose a total phaseout as of 2009. One third, 3.334 GW, of the existing nuclear capacity will be phased out as of 1999. Another third will be phased out as of 2004 and the last third as of 2009, meaning, as mentioned above, a total phaseout as of 2009. This scenario represents a fairly realistic time schedule if the parliament decides to fulfill the literal date pictured in the referendum. A possible discrepancy between our time schedule and other realistic time schedules that also fulfill the date pictured in the referendum is of no importance to the general conclusions we make, although the specific numbers may differ in each case. In Table 5.2 the estimated levels and growth of the main variables in Scenario 1 are shown.

Table 5.2 Summary of Scenario 1 - Phaseout of nuclear power.

	1991	2000	2010	2020
Electricity price (industry) (1995 SEK/kWh)	0.21	0.32	0.27	0.27
Electricity use (TWh)	132	127	160	188
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	43.5	0.0	0.0
Natural gas	0.0	1.5	78.1	105.6
Fossil fuels	8.1	12.8	12.8	13.1
Biomass	0.1	10.0	10.0	10.0
Imports	0.0	0.0	0.0	0.0
Emissions				
CO ₂ (Million tons)	31	52	90	108
Implicit CO ₂ tax (1995 SEK/kg CO ₂)	0.0	0.0	0.0	0.0
Marginal generation source	Biomass	Biomass	Natural gas	Natural gas
Present value of objective function (Billions of 1995 SEK)	- 117			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.

Note: Fossil fuels is an aggregate of oil and coal.

Note: Biomass is an aggregate of wooden chips and peat.

Note: Present value of the objective function has been normalized to zero in the base case.

The present value of the objective function is in this scenario 117 billion SEK smaller than in the base case. The interpretation of this result is that the cost of a total phaseout, following the time schedule outlined above, is 117 billion SEK for the Swedish society as a whole. The electricity price rises sharply around the year 2000 compared to the base case. The reason is that demand is growing, and when the nuclear power is phased out the drop in electricity production creates a scarcity since not enough capacity can be added at this point in time. This scarcity drives the price to a fairly high level. The assumption is that new natural gas plants can not come into operation until after the turn of the century since lead times for the

infrastructure needed to distribute this type of power in general are very long.³⁸ As for other generation sources they are just not profitable at the sustaining price level. When new capacity then comes into production the price returns to a lower level. The electricity price then follows the pattern in the base case which is explained by the fact that the same technology is run on the margin in the two cases.

Total generation will be 127 TWh by the year of 2000, 160 TWh by the year of 2010, and 188 TWh by the year of 2020. These figures, when compared to their counterparts in the base case, show that the total generation of electricity is affected by the phaseout around the turn of the century. This is due to the time needed for new capacity to become available. The nuclear power is substituted by natural gas implying a sharp increase in CO₂ emissions over the time-horizon of the model. In fact they rise much faster than they do in the base case, were they rose by 155 % between 1991 and 2020, compared to 248 % during the same time-period in this scenario.

5.5.2 Scenario 2 - Stabilize CO₂ at the 1990 level

In the second policy scenario the effects of fulfilling the commitment not to increase CO₂ emissions above 1990 levels are studied. Nuclear power is allowed to continue to operate in this scenario in order to analyze the pure effects of implementing the CO₂ commitment.

Our interpretation of the consequences for the energy sector of the commitment not to increase CO₂ emissions above 1990 levels (for the society as a whole) is that the energy sector should not emit more carbon dioxide in any subsequent year than it has in the year of 1990. In brief, the energy sector shall do its share.³⁹ Consequently we do not allow the CO₂ emissions in the energy sector described in our model to exceed the 1990 level, which then was equal to 31 million tons of CO₂. In Table 5.3 the estimated levels and growth of the main variables in Scenario 2 are shown.

³⁸ The lead times in question consist of both the time for obtaining all required permissions to build, as well as actual construction time of the plants and the infrastructure.

³⁹ The transport sector is the other large emitter of CO₂. Since it is expensive to reduce CO₂ emissions in both the energy sector and the transportation sector one can not motivate that one sector of the two should carry a smaller share of the load to fulfill the national goal of maintaining CO₂ emissions at the 1990 level.

Table 5.3 Summary of Scenario 2 - Stabilize CO₂ at the 1990 level.

	1991	2000	2010	2020
Electricity price (industry) (1995 SEK/kWh)	0.21	0.29	0.36	0.52
Electricity use (TWh)	132	138	143	147
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	65.2	65.2	65.2
Natural gas	0.0	1.5	3.1	3.1
Fossil fuels	8.1	9.1	3.7	0.0
Biomass	0.1	3.5	10.0	10.0
Imports	0.0	0.0	2.1	9.3
Emissions				
CO ₂ (Million tons)	31	31	31	31
Implicit CO ₂ tax (1995 SEK/kg CO ₂)	0.0	0.09	0.18	0.50
Marginal generation source	Biomass	Biomass	Imports	Imports
Present value of objective function (Billions of 1995 SEK)	-112			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.

Note: Fossil fuels is an aggregate of oil and coal.

Note: Biomass is an aggregate of wooden chips and peat.

Note: Present value of the objective function has been normalized to zero in the base case.

As can be seen in Table 5.3 the present value of the objective function in this scenario is 112 billion SEK smaller than in the base case, which indicates that the cost of fulfilling the CO₂ commitment is smaller than the cost of the nuclear phaseout in Scenario 1.

Electricity prices will rise sharply in the long run and electricity use (or generation) will not increase as fast as in the base case, since the growing demand cannot be met by other means than price increases due to the CO₂ restrictions. The electricity price in the industry will be 0.29 SEK/kWh by the year of 2000, which is higher than in the base case. But by the years of

2010 and 2020 the price will increase even further, namely to 0.36 and 0.52 SEK/kWh respectively.⁴⁰ The reason being that the only way to hold back the growing demand is to raise the prices since no economic viable generation source can be used to meet the increasing demand due to the CO₂ condition. The CO₂ restriction becomes more and more binding over time as the economy grows. This implies that the implicit CO₂ tax has to grow accordingly, in order to keep the prevailing emission level. It can be noted, as a comparison to the implicit CO₂ taxes in the table, that actual CO₂ taxes for manufacturing industries in Sweden were about 0.08 SEK/kg of emitted CO₂ in 1995. Furthermore, it can be seen that the restriction of 10 TWh on biomass production is binding by the year of 2010.

The total generation figures are fairly constant over time, increasing from 132 TWh by the year of 1991 to 147 TWh by 2020. Compared to the base case, where the total generation of electricity rose sharply, this is a very modest development, to say the least. In the year of 2000 the configuration of the sources of generation in this scenario is approximately the same as in the base case. The configuration of the sources of generation is fairly constant over time in this scenario. The only changes are that fossil fuels partly are substituted by natural gas and that biomass and imports grow.

5.5.3 Scenario 3 - Phaseout nuclear power and stabilize CO₂ at the 1990 level

The third policy scenario is a combination of Scenario 1 and 2, i.e. the impact of phasing out nuclear power in conjunction with fulfilling the commitment not to increase CO₂ emissions above 1990 levels. This scenario includes three of the four restrictions the Swedish parliament has imposed on the future energy policy discussed in the introduction, namely the restrictions that concern nuclear power, hydro power and CO₂ emissions. The time schedule for the nuclear phaseout and the restrictions on the CO₂ emissions are exactly the same as in Scenario 1 and 2, respectively. In Table 5.4 the estimated levels and growth of the main variables in Scenario 3 are shown.

⁴⁰ The estimated prices are likely high enough to be perceived as a violation of the stated policy objective, *that electricity should be supplied on internationally competitive terms.*

Table 5.4 Summary of Scenario 3 - Phaseout nuclear power and stabilize CO₂ at the 1990 level.

	1991	2000	2010	2020
Electricity price (industry) (1995 SEK/kWh)	0.21	0.34	0.68	0.86
Electricity use (TWh)	132	124	96	94
Generation (TWh)				
Hydro	59.1	59.1	59.1	59.1
Nuclear	65.2	43.5	0.0	0.0
Natural gas	0.0	1.5	17.4	15.9
Fossil fuels	8.1	9.7	0.0	0.0
Biomass	0.1	10.0	10.0	10.0
Imports	0.0	0.0	9.3	9.3
Emissions				
CO ₂ (Million tons)	31	31	31	31
Implicit CO ₂ tax (1995 SEK/kg CO ₂)	0.0	0.16	0.71	1.34
Marginal generation source	Biomass	Biomass	Imports	Imports
Present value of objective function (Billions of 1995 SEK)	-492			

Note: The prices are at the user, net of losses, and excluding V.A.T. and electricity tax per kWh.

Note: Fossil fuels is an aggregate of oil and coal.

Note: Biomass is an aggregate of wooden chips and peat.

Note: Present value of the objective function has been normalized to zero in the base case.

It is obvious from Table 5.4 that the present value of the objective function in this scenario is dramatically lower than in the base case. The cost of a total phaseout, following the time schedule outlined above in conjunction with fulfilling the CO₂ commitment is 492 billion SEK for the Swedish society as a whole. This is more than four times the cost of phasing out nuclear power when no restrictions were imposed on the CO₂ levels.

Electricity prices will rise sharply and electricity use (or generation) will decline severely since the drop in nuclear production cannot be replaced by any other inexpensive source due to the restrictions on the CO₂ emissions. The electricity prices in the industry will be 0.34 SEK/kWh by the year of 2000, 0.68 SEK/kWh by the year of 2010, and 0.86 SEK/kWh by the year of 2020.⁴¹ A considerable increase for every year compared to the base case.

It can further be noted that the implicit CO₂ tax has to be larger in each year as compared to Scenario 2. The reason being that the CO₂ constraint is even more binding in this scenario due to the nuclear phaseout.

The configuration of the generation sources vary over time. Fossil fuels are substituted by natural gas, nuclear power is gradually phased out, and imports start to take place. In the year of 2000 electricity will mainly be generated by hydro power, nuclear power, fossil fuels, and biomass. In the year of 2010 electricity will mainly be generated by hydro power, natural gas, and biomass. A substantial amount of electricity will also be imported.

In this scenario it is important to point out that the driving force over time is an exogenous income growth in the economy. Since the income growth is exogenous, independent of electricity prices and electricity supply, there is no feedback from the output of the model into the income growth. However, this is not a major flaw when the conditions are fairly normal. Normal in the sense that we have a scenario that we think is at least somehow consistent with the exogenous income growth. It is our strong belief that this is the case in Scenario 1 and 2. But in this scenario, Scenario 3, we get very high prices of electricity and a substantially smaller total generation of electricity. This would probably affect the income growth negatively, and therefore the realism in having the same income growth in Scenario 3 as we have in the previous scenarios could be discussed. However since we want to be able to analyze the pure effects of the restrictions imposed by the parliament we let "other things be equal", including the income growth.

⁴¹ The estimated prices are definitely high enough to be perceived as a violation of the stated policy objective, *that electricity should be supplied on internationally competitive terms.*

5.6 Sensitivity analysis

5.6.1 The value of waiting

In the scenarios above we have followed the decisions already taken concerning Swedish energy policy. Given the assumptions and the model we have used, it has been shown that it obviously is expensive to phase out nuclear power in Sweden, especially if the CO₂ commitment is to be met at the same time. An interesting variation to the scenarios we have studied is to examine what happens if the phaseout is postponed for five or ten years. What we have in mind is a phaseout of nuclear power that follows the same pattern as previously, but with the start-date moved five or ten years into the future.

The results from postponing the phaseout for five years in Scenario 1 show that the saving is equal to 37 billion SEK, measured as the change in the net present value of the objective function. If the nuclear phaseout is postponed another five years the saving turns out to be an additional 24 billion SEK, or 61 billion SEK in total. This implies that the costs of a nuclear phaseout are cut in half if the decision is postponed for 10 years.

Since the really hard-line phaseout case is Scenario 3, where the CO₂ commitment is in effect, it is interesting to examine what the potential savings are from a postponement in this case. If the nuclear phaseout is not started until five years later than according to the original plan, the result is a saving of 76 billion SEK. A postponement of five additional years result in a saving of another 70 billion SEK, or 146 billion SEK in total. From this it is clear that the savings in the CO₂ commitment scenario are lower measured as shares of the total cost, compared to the corresponding savings in Scenario 1, although the savings are much larger in absolute terms.

5.6.2 Varying some key parameters

Several of the assumptions made in the model might be crucial for the results in the scenarios. We have changed a few key parameters in order to evaluate some of the critical assumptions.

The first assumption concerns the discount rate. The question asked is how sensitive the results are to a 1% change in the discount rate. When a 4 % discount rate is used instead of 5 %, the cost of phasing out nuclear power increases by 18 billion SEK, when no restrictions on the CO₂ emissions are imposed, and by 128 billion SEK, when the restrictions on the CO₂

emissions are in effect. On the other hand, if a 6 % discount rate is used instead of a 5 % discount rate, the cost of phasing out nuclear power decreases by 14 billion SEK, when no restrictions on the CO₂ emissions are imposed. Using the 6 % discount rate decreases the cost of phasing out nuclear power by 97 billion SEK, when the restrictions on the CO₂ emissions are imposed. This indicates that the discount rate is very important to the outcome.

The second assumption that is changed concerns the growth rate of the economy. When the model is run with an annual growth rate of 1% instead of with 2%, the cost of a nuclear phaseout drops by only 2 billion SEK, when no restrictions on the CO₂ emissions are in effect, and by as much as 234 billion SEK when the restrictions on the CO₂ emissions are imposed. Thus, the cost of a nuclear phaseout might be highly dependent upon the growth of the economy.

And finally, the assumption that only 10 TWh of electricity can be produced annually from biomass is changed to 20 TWh, keeping the cost of electricity from new biomass constant. As before the constraint is valid from the year 2000. The result of this is that the cost of phasing out nuclear power, as in Scenario 1, is reduced by 0.3 billion SEK, and the cost of phasing out nuclear power drops by 7 billion SEK, when the restrictions on the CO₂ emissions are imposed. Apparently a doubling of possible electricity production from biomass has no great effect on the costs of a nuclear phaseout. This is also the case for increases of similar magnitude in import capacity, given unchanged electricity prices abroad.

5.7 Concluding remarks

In order to put the costs of a nuclear phaseout into perspective it is interesting to compare the cost with another figure such as the GDP of Sweden. The cost of a phaseout is approximately 7 % of the GDP in 1995, when no restrictions are made on the CO₂ emissions. For the case where the CO₂ emissions are restricted to 1990 levels, the cost of a nuclear phaseout is 30 %, when measured as a share of GDP. Obviously this indicates that the cost of a nuclear phaseout is bound to have a substantial impact on the Swedish economy. It is also interesting to observe that the results in this study are very close to the ones presented by Nordhaus (1995). Especially since our modeling approaches are different.

Although the costs referred to above are substantial one should note that they are based on a frictionless economy, and are thus likely to underestimate the actual costs to society. We

know that the economy is not frictionless and that prices and wages do not adapt immediately to changes or shocks.

Another aspect of this is the fiscal effects that will follow a nuclear phaseout. The costs of a nuclear phaseout are likely to significantly increase the Swedish public debt, which may lead to higher costs for borrowing money, especially since the public debt already is large. This in turn may lead to additional costs to society, for example in the form of increased deadweight losses from the collection of higher taxes. Together this indicates that there are macro-economic effects that likely will add more to the costs estimated in this study.

All in all this points in the direction that, even when the condition of inexpensive electricity to the energy intensive industry is disregarded, the two goals of phasing out nuclear power and restricting CO₂ emissions are almost mutually exclusive to fulfill, or at least extremely expensive in terms of direct costs and industry restructuring. From this follows that the political conditions are not likely to persevere. It is probable that some condition will have to be relaxed and it may well be the case that the CO₂ emissions are bound to increase above 1990 levels in order to limit the costs of a phaseout. An interesting issue is then how this would affect the international reputation of a country, known for its environmental consciousness, that has committed itself to limit the emissions of CO₂ to a certain level.

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Appendix 5.A - Production costs

5.A.1 Variable production costs

Three different categories of electricity production are identified: hydro power, condense power, and combined heat and power. For heat production the main category is ordinary combustion. As for electricity production by condense power there are in turn five different types of plants represented in the model: nuclear, coal, heavy oil (oil 5), light oil (oil 1), and natural gas. The corresponding plants for combined heat and power are: coal, oil 5, chips, peat, and natural gas. Estimates of the variable costs for electricity production associated with the different plants are shown in Table 5.A.1.

Table 5.A.1 Variable costs in electricity production.

	Fuel costs Öre/kWh ⁴²	Non-fuel costs Öre/kWh
<u>Condense power</u>		
Nuclear	3.9	3.3
Coal	9.7	1.7 - 7.2
Oil 5	16.2	1.3
Oil 1	33.3	2.6
Natural gas	15.6	2.2
<u>Combined heat and power</u>		
Coal	12.1	1.3 - 7.8
Oil 5	19.7	1.3
Chips	23.7	1.3
Peat	20.4	1.3
Natural gas	18.7	1.3

Note: All costs are at the user in 1995 SEK.

Note: The span in non-fuel costs for coal is due to different abatement technologies.

Note: Total variable costs, i.e. fuel plus non-fuel costs, are referred to as VC in Appendix 5.D.

In the model there are no fuel costs or non-fuel costs associated with electricity produced by hydro power. This category of electricity production is only levied with the specific energy taxes that are associated with each category respectively.

⁴² 100 öre = 1 SEK

Electricity may also be imported in the model. The cost of this is assumed to be 36 öre/kWh at the user.

Heat produced by ordinary combustion can in the model originate from one of six types of plants: coal, oil 5, chips, peat, waste, and natural gas. The associated variable costs for these heat plants are displayed in Table 5.A.2.

Table 5.A.2 Variable costs in heat production.

	Fuel costs Öre/kWh	Non-fuel costs Öre/kWh
<u>Ordinary combustion</u>		
Coal	4.7	1.4 - 5.0
Oil 5	7.6	0.7
Chips	9.1	1.5
Peat	7.9	1.5
Waste	8.7	2.9
Natural gas	9.8	0.7

Note: All costs are at the user in 1995 SEK.

Note: The span in non-fuel costs for coal is due to different abatement technologies.

Note: Total variable costs, i.e. fuel plus non-fuel costs, are referred to as *VC* in Appendix 5.D.

5.A.2 Fixed production costs

Since one important part of the investment decision in the model is associated with the investment cost for different production categories it is vital to include data on this. For the different electricity producing plants the investment costs as well as the fixed annual maintenance costs associated with the plants are shown in Table 5.A.3. The corresponding fixed costs for heat production are displayed in Table 5.A.4.

Table 5.A.3 Fixed costs in electricity production.

	Investment costs SEK/kW	Annual maintenance costs SEK/kW
<u>Condensing power</u>		
Nuclear	15 000	225
Coal	11 500 - 15 500	170 - 230
Oil 5	15 000	220
Oil 1	8 500	125
Natural gas	6 500	95
<u>Combined heat and power</u>		
Coal	16 000 - 19 000	240 - 285
Oil 5	17 000	250
Chips	16 000	240
Peat	16 000	240
Natural gas	7 500	110

Note: All costs are in 1995 SEK.

Note: The span in costs for coal is due to different abatement technologies.

Note: Investment costs are referred to as *IC* in Appendix 5.D.

Note: Annual maintenance costs are referred to as *AMC* in Appendix 5.D.

Table 5.A.4 Fixed costs in heat production.

	Investment costs SEK/kW	Annual maintenance costs SEK/kW
<u>Ordinary combustion</u>		
Coal	2 900 - 4 200	45 - 75
Oil 5	2 500	35
Chips	2 900	45
Peat	2 900	45
Waste	5 000	75
Natural gas	1 300	19

Note: All costs are in 1995 SEK.

Note: The span in costs for coal is due to different abatement technologies.

Note: Investment costs are referred to as *IC* in Appendix 5.D.

Note: Annual maintenance costs are referred to as *AMC* in Appendix 5.D.

Appendix 5.B - Parameter values

Real income growth

$$\Delta Y = 2 \%$$

Discount rate

$$r = 5 \%$$

Table 5.B.1 Price and income elasticities.

Own price elasticity	Cross price elasticity	Income elasticity
$\varepsilon_{HH} = -0.3$	$\varepsilon_{HF} = 0.1$	$\varepsilon_Y^H = 0.7$
$\varepsilon_{VV} = -0.3$	-	$\varepsilon_Y^V = 0.0$
$\varepsilon_{UU} = -0.3$	$\varepsilon_{UB} = 0.03$	$\varepsilon_Y^U = 0.7$
$\varepsilon_{W1W1} = -0.3$	-	$\varepsilon_Y^{W1} = 0.7$
$\varepsilon_{W2W2} = -0.3$	-	$\varepsilon_Y^{W2} = 0.7$
$\varepsilon_{W3W3} = -0.3$	-	$\varepsilon_Y^{W3} = 0.7$

Accessibility of installed capacity

Electricity: $\alpha_e = 0.80 - 0.94$

Heat: $\alpha_h = 0.90 - 1.00$

Depreciation rate of installed capacity

Net after productivity growth: $\delta = 0$

Table 5.B.2 Load periods.

τ	Hours per year	Share of the demand
1	450	0.074
2	1200	0.182
3	7110	0.744

Heat factors in cogeneration plants

Natural gas: $\gamma_n = 1.00$

Other fuels: $\gamma_o = 1.27$

Distribution losses

Electricity: $\sigma_e = 0.07$

Heat: $\sigma_h = 0.09$

Price of imported electricity

Net after losses: $P_{IMP} = 36 \text{ öre/kWh}$

Restrictions on imports of electricity

Before losses: $\hat{IMP}_t = 10.0 \text{ TWh}$

Appendix 5.C - Sensitivity analysis

In Table 5.C.1 the effects of different scenarios measured as changes in the present value of the objective function are displayed. For each set of scenarios, the present value of the objective function has been normalized to zero in the base case, i.e. when no nuclear phaseout and no restrictions on CO₂ emissions are enforced. The present value of the objective function is measured in billions of 1995 SEK.

Table 5.C.1 Sensitivity analysis.

	No nuclear phaseout	Nuclear phaseout
<u>Key scenarios</u>		
No restrictions on CO ₂	0	- 117
CO ₂ limited to 1990 levels	- 112	- 492
<u>Phaseout postponed 5 years</u>		
No restrictions on CO ₂	0	- 80
CO ₂ limited to 1990 levels	- 112	- 416
<u>Phaseout postponed 10 years</u>		
No restrictions on CO ₂	0	- 56
CO ₂ limited to 1990 levels	- 112	- 346
<u>Discount rate 4 %</u>		
No restrictions on CO ₂	0	- 135
CO ₂ limited to 1990 levels	- 147	- 620
<u>Discount rate 6 %</u>		
No restrictions on CO ₂	0	- 103
CO ₂ limited to 1990 levels	- 85	- 395
<u>Economic growth 1 %</u>		
No restrictions on CO ₂	0	- 115
CO ₂ limited to 1990 levels	- 21	- 258
<u>10 TWh new biomass⁴³</u>		
No restrictions on CO ₂	0	- 117
CO ₂ limited to 1990 levels	- 109	- 484

⁴³ Defined as a possibility to expand production with an additional 10 TWh as from the year 2000.

Appendix 5.D - Model specification⁴⁴

The objective function⁴⁵

$$\begin{aligned}
 OBJ = & \sum_{t=1}^9 \frac{5}{(1+r)^{5(t-1)}} \left\{ \int_0^{V_t^*} P_V(V_t) dV_t + \int_0^{H_t^*} P_H(H_t) dH_t + \int_0^{U_t^*} P_U(U_t) dU_t + \int_0^{HP_t^*} P_{HP}(HP_t) dHP_t \right. \\
 & + \int_0^{EB_t^*} P_{EB}(EB_t) dEB_t + \int_0^{B_t^*} P_B(B_t) dB_t + \int_0^{F_t^*} P_F(F_t) dF_t \\
 & - (1-\sigma_e) \sum_{\tau} \sum_f \sum_a VC_{efat} K_{efat}^{\tau} T^{\tau} - (1-\sigma_e) \sum_{\tau} \sum_f \sum_a VC_{cfat} K_{cfat}^{\tau} T^{\tau} \\
 & - (1-\sigma_h) \sum_{\tau} \sum_f \sum_a \sum_w VC_{hfawt} K_{hfawt}^{\tau} T^{\tau} \\
 & - (1-\sigma_h) \sum_{\tau} \sum_w VC_{EBt} K_{EBwt}^{\tau} T^{\tau} - (1-\sigma_h) \sum_{\tau} \sum_w VC_{HPt} K_{HPwt}^{\tau} T^{\tau} \\
 & - \sum_f \sum_a AMC_{efat} \bar{K}_{efat} - \sum_f \sum_a AMC_{cfat} \bar{K}_{cfat} - \sum_f \sum_a \sum_w AMC_{hfawt} \bar{K}_{hfawt} \\
 & - \sum_w AMC_{EBt} \bar{K}_{EBwt} - \sum_w AMC_{HPt} \bar{K}_{HPwt} - 0.2 \sum_f \sum_a IC_{efat} I_{efat} \\
 & - 0.2 \sum_f \sum_a IC_{cfat} I_{cfat} - 0.2 \sum_f \sum_a \sum_w IC_{hfawt} I_{hfawt} - 0.2 \sum_w IC_{EBt} I_{EBwt} \\
 & \left. - 0.2 \sum_w IC_{HPt} I_{HPwt} - P_{B_t} B_t - P_{F_t} F_t - P_{IMP_t} (1-\sigma_e) (IMP_t^1 + IMP_t^2 + IMP_t^3) - TAX_t \right\}
 \end{aligned}$$

⁴⁴ Besides the restrictions stated in this appendix, there are some additional generation and capacity restrictions which are not of general importance and therefore not stated here.

⁴⁵ The market clearing quantities of the variables in question are denoted by star. The variable TAX represents total taxes collected in the energy sector. It is important to point out that the changes in the present value of the objective function displayed in the scenarios above, have been calculated by using the objective function OBJ, taking into account that total taxes collected in the energy sector vary between different scenarios.

Subject to:

Market clearing condition - Electricity market

$$\begin{aligned} & (1-\sigma_e) \sum_f \sum_a K_{efa}^\tau T^\tau + (1-\sigma_e) \sum_f \sum_a \sum_w K_{efaw}^\tau T^\tau + (1-\sigma_e) IMP_t^\tau \\ & = V_t^\tau + H_t^\tau + U_t^\tau + HP_t^\tau + EB_t^\tau, \quad \text{for } \tau = 1, 2, 3 \text{ and } t = 1, 2, \dots, 9 \end{aligned}$$

Market clearing conditions - Heat markets

$$(1-\sigma_h) \sum_f \sum_a \gamma K_{efa1}^\tau T^\tau + (1-\sigma_h) \sum_f \sum_a K_{hfa1}^\tau T^\tau = W1_t^\tau, \quad \text{for } \tau = 1, 2, 3 \text{ and } t = 1, 2, \dots, 9$$

$$(1-\sigma_h) \sum_f \sum_a \gamma K_{efa2}^\tau T^\tau + (1-\sigma_h) \sum_f \sum_a K_{hfa2}^\tau T^\tau = W2_t^\tau, \quad \text{for } \tau = 1, 2, 3 \text{ and } t = 1, 2, \dots, 9$$

$$(1-\sigma_h) \sum_f \sum_a \gamma K_{efa3}^\tau T^\tau + (1-\sigma_h) \sum_f \sum_a K_{hfa3}^\tau T^\tau = W3_t^\tau, \quad \text{for } \tau = 1, 2, 3 \text{ and } t = 1, 2, \dots, 9$$

Capacity conditions - Electricity production

\bar{K}_{efa1} exogenously given,

$$\bar{K}_{efa} = (1-\delta) \bar{K}_{efa-1} + I_{efa-1}, \quad \text{for } t = 2, 3, \dots, 9 \text{ and } \forall f \text{ and } a$$

$$K_{efa}^\tau \leq \alpha_{efa} \bar{K}_{efa} \quad \text{for } \tau = 1, 2, 3, \quad t = 1, 2, \dots, 9 \text{ and } \forall f \text{ and } a$$

Emission constraints

$$\begin{aligned} EMI_t = & \sum_\tau \sum_f \sum_a \theta_{efa} K_{efa}^\tau T^\tau + \sum_\tau \sum_f \sum_a \sum_w \theta_{efa} (1+\gamma_{fa}) K_{efaw}^\tau T^\tau + \sum_\tau \sum_f \sum_a \sum_w \theta_{hfa} K_{hfa}^\tau T^\tau, \\ & \text{for } t = 1, 2, \dots, 9 \end{aligned}$$

$$EMI_t \leq \hat{EMI}_t, \quad \text{for } t = 1, 2, \dots, 9$$

\hat{EMI}_t exogenously given

Import constraints

$$IMP_t^1 + IMP_t^2 + IMP_t^3 \leq \hat{IMP}_t, \quad \text{for } t = 1, 2, \dots, 9$$

\hat{IMP}_t exogenously given

Part 3

Residential electricity demand

Chapter 6

Electricity Demand - A Study of the Swedish Residential Sector

6.1 Introduction

Several studies on residential electricity demand have been carried out using Swedish data. One example is Nilsson (1989). A characteristic of most of the earlier studies is that they used time-series data for aggregated energy use, such as GNP, disposable income etc., in their estimations. This could lead to certain problems: The precision in the estimation might be limited due to the restricted amount of observations. These time-series commonly have only one observation per year for each variable, and the observed series are usually of very limited length. Another problem is that the underlying theory is based on individual agents behavior, and it is only under very strict assumptions that the theory holds for aggregates of individuals or households.

One way to avoid these problems is to use disaggregated data from individual households. A trend that can be seen in recent demand studies is that as more detailed and reliable data has been made available, an increasing number of the studies and estimations are based on disaggregated data. Bohi (1981) has conducted an extensive survey of demand studies made on electricity, and one important conclusion from his survey is that the results tend to be more precise and accurate the more disaggregated the underlying data is. In the case of Sweden there has not been made any electricity demand study based on micro data that is known by the author.

The purpose of this study is to estimate the residential demand for electricity in Sweden using disaggregated micro data, and to answer the following two questions: First, how large is the magnitude of a price effect on electricity demand? Secondly, is the detailed information used in these estimations enough to explain the variations in individual households' electricity demand or is additional information (e.g. socio-economic data) needed on consumers' behavior and habits?. Similar studies using micro data have been made before in other countries. One example is a study by Morss and Small (1989). They estimated a demand model for electricity based on cross-sectional data from more than 34 000 households in the U.S. The data was collected in 1984. Another study was carried out by Parti and Parti (1980) using data from more than 5000 individual households in the U.S. One geographically more closely related study was carried out by Eitheim et. al. (1989) on data from Norway.

6.1.1 Important factors behind household electricity demand

What the household demands is not the electricity in itself, or the different appliances that use electricity, instead it is the services that they produce, in the shape of for example heat, light and comfort. It is therefore reasonable to derive the household's direct demand for electricity from the stock of different appliances possessed by the household, as well as from other household specific characteristics.

One way to model different factors' influence on electricity demand is the following: Household income, electricity price, and other variables influence electricity demand both directly and indirectly: Indirectly through the households purchases of appliances that use electricity, and directly through the household specific behavior that influences electricity use given the stock of electrical appliances. The direct influence on electricity demand is modeled:

$$E = f(A, B, Y, P, Z) \quad (1)$$

where the demand for electricity (E) is a function of appliance ownership (A), variables representing household members' behavior (B), such as indoor temperatures maintained in different rooms, household income (Y), electricity price (P), and other variables (Z). In the short run the appliance stock (A) is assumed to be fixed, but in the long run it can be adjusted, thereby reflecting the household's adjustment to changes in price and income. The long run

effect is an indirect influence on electricity demand and in order to capture this, appliance ownership (A) is modeled as a function of income and electricity price:⁴⁶

$$A = g(Y, P). \quad (2)$$

A similar line of reasoning is used for household members' behavior (B), namely that in the long run behavior is a function of income and electricity price, which can then be written accordingly:

$$B = h(Y, P). \quad (3)$$

Substitution of equations (2) and (3) into equation (1) yields:

$$E = f[A(Y, P), B(Y, P), Y, P, Z] \quad (4)$$

which then models both the direct and indirect influence on electricity demand from income and electricity price, as well as the influence from other household specific characteristics. The estimations following this way of modeling electricity demand will be discussed more in detail in section 6.3.

The organization of the chapter is as follows: In section 6.2 the data is described and some decisions regarding which variables to use later in the regressions are made. Section 6.3 deals mainly with the estimation of, and the results from, the electricity demand model. The chapter ends with section 6.4 where the main findings are discussed and some concluding remarks are made.

6.2 Data

The data material used in this study consists of very detailed information about individual household characteristics. The data is cross-sectional and was collected in a survey made by Vattenfall AB in 1986. The original survey included 257 questions on a wide range of topics.

⁴⁶ The appliance ownership variables are dummy variables taking the values of either 0 or 1, where 1 indicates that the specific appliance is present in the household.

The data base consists of around 4000 observations collected from households situated in different parts of Sweden, specifically from the towns of Vännäs, Kalix and Tierp.

6.2.1 The variables

A brief description of the data base shows that, among several other topics, the following is covered:

- Single family or multi family housing.
- Number of household members.
- Type of space heating method; oil, electricity or other.
- Measures taken to insulate house.
- Other measures taken to conserve electricity.
- The present stock of electrical appliances; refrigerator, freezer, washing machine, sauna etc.
- Average temperature in different rooms.
- Local weather characteristics, i.e., heating degree days.
- Household income.
- Electricity price.

A list of the variables and their abbreviations is presented in Appendix 6.C. As can be seen above the material consists mainly of "hard facts" that are easily observable, such as appliance stock and household income. According to existing theories this should provide us with enough information in order to successfully estimate residential electricity demand. The level of this success can be measured in the share of variation in electricity consumption that can be explained by the variables in the regression equation. With this extensive data base it is justified to believe that we should achieve a high level of explanatory power. However, one part of the literature (see for example Schipper et al. 1992) argues that this information is not enough in order to understand the variations in electricity demand, and that additional data concerning "soft facts", or socio-economic facts, i.e. observations on consumers preferences and their behavior, is essential. Since the variables in the data base used in this study are primarily of the "hard" type it will be interesting to see whether enough information is provided to explain the variations in electricity consumption, or if observations on additional variables are desirable.

Two comments about the electricity price are important at this stage: In order to establish relations between electricity demand and electricity price we need variations among the

observations of the price. The electricity price is regionally differentiated in Sweden and it is therefore possible to have variations among the price observations, even though the degree of variation among the actual observations is not very large. The regional price differentiation has a long history and one can safely assume that consumers have had plenty of time to adjust their behavior accordingly. The other comment concerns the fact that the regional differentiation of prices in practice mean that every household in a certain region in Sweden face the same tariff structure. As a result from this perfect correlation between location and electricity price a problem for our purposes arises, namely that the price variable will contain every town-specific characteristic that has not been explicitly identified elsewhere.

The fact that the regional price differentiation has a long history, implying that the households are in long run equilibrium with their equipment stock and other household specific variables, together with the cross-sectional character of the data set, means that the elasticities discussed later in this paper will reflect only the long run effects.

6.2.2 Description of the material

In this section the material in the data base is described thoroughly and an effort is made to draw conclusions about which variables that should be included in the estimation of the demand model in section 6.3. The first step in order to make the picture clearer is to divide the material into two separate groups. One group consisting of the households from multi family housing, and the other group with the households from single family housing.

6.2.2.1 Variations in the material

In order to establish relations between the variables we need variations in the material. If there is no variation among the factors that are used to explain the variation in electricity demand through the regression process, it is impossible to establish a relationship between the factors. Therefore the main purpose of this and the next section is to decide on which variables that are likely to contribute the most to explain electricity demand. The following tables contain information about the saturation level of different electrical appliances and measures taken to conserve electricity. The variations in the material are represented by the standard deviations. The first table shows the stock and the variations in electrical appliances for households in single family housing.

Table 6.1 Ownership of Electrical Appliances, Single Family Housing

Appliance	Mean	Standard Deviation
STOVE	0.999	0.020
FRIDGE	0.999	0.015
FREEZER	0.994	0.078
FREEZER2	0.592	0.492
FREEZER3	0.091	0.287
FAN	0.984	0.126
DISHWASH	0.582	0.493
WATERHEAT	0.584	0.493
WASHER	0.949	0.218
DRYER	0.333	0.471
TUMBLE	0.111	0.314
INFRA	0.026	0.160
SAUNA	0.469	0.499
CARHEAT	0.679	0.467

It is clear that several of the different appliances are present in almost every household. Stove, refrigerator, freezer, kitchen-fan, and washing-machine all have saturation levels above 90 %. In order to avoid the problem with an almost perfect linear relationship between these variables and the constant term in the estimations later on, the decision is made to drop all variables with a saturation level above 90 %. For infra-heat and a third freezer the case is the opposite. They are present in less than 3 % and 10 % of the households, respectively. Since these two variables have both a low mean and standard deviation their influence as explanatory variables is likely to be low and they will therefore be excluded from the regression runs. The remaining appliances have a mean that is low enough for them to avoid a close linear relationship with the constant term and a standard deviation that is high enough to indicate that they can have some explanatory power as independent regression variables.

Table 6.2 Ownership of Electrical Appliances, Multi Family Housing

Appliance	Mean	Standard Deviation
STOVE	0.997	0.056
FRIDGE	0.999	0.025
FREEZER	0.849	0.357
FREEZER2	0.133	0.339
FREEZER3	0.011	0.103
FAN	0.546	0.498
DISHWASH	0.078	0.269
WATERHEAT	0.032	0.177
WASHER	0.271	0.445
DRYER	0.065	0.247
TUMBLE	0.012	0.109
INFRA	0.001	0.035
SAUNA	0.011	0.106
CARHEAT	0.377	0.484

For multi family households the situation is different. Only a stove and a refrigerator are present in almost every household. They will therefore not be included as separate variables in the regression equation. Several of the appliances are present very infrequently, as indicated by a mean below 10 %, and will not be included at all. The appliances that have a reasonably high saturation level and/or standard deviation are; freezer number one and two, kitchen-fan, washing machine, dryer, and car heater. These appliances will be included as dummy variables in the regression in section 6.3.

The next table shows means and standard deviations for measures taken to conserve electricity. Regarding these variables there were no data available for multi family housing.

Table 6.3 Measures to Conserve Electricity, Single Family Housing

Conservation Measure	Mean	Standard Deviation
INSULATION	0.842	0.366
DOORLIST	0.545	0.498
SEALED	0.097	0.296
INSULWALL	0.174	0.379
INSULROOF	0.226	0.418
THREEGLASS	0.155	0.362
WOODFURNACE	0.136	0.343
GROUND INSULATED	0.062	0.242

The same line of reasoning is followed to find candidates for the regression equations among the measures taken to conserve electricity. None of the measures have a mean that is high enough to indicate problems with an almost perfect linear relationship with the constant term in the estimations of the regression equations to follow. The measures extra insulation, door lists, and insulated roof appear frequently enough among the households, and have a relatively high level of variation, to distinguish themselves as interesting candidates for the regression equations.

Table 6.4 Other Variables, Single Family Housing

Variable	Mean	Standard Deviation
ELPRICE (öre/kWh) ⁴⁷	0.308	0.061
ELCONS (kWh/year)	25,386.0	12,852.0
INCOME (SEK 1986)	168,282.0	66,669.0
ELHEAT	0.519	0.499
NUMBER (Persons/HH)	2.986	1.215

In order to establish price and income elasticities, variations in the material is needed for the same reasons as argued earlier. This appears to be no problem for the income variable, but the variations in the price of electricity is very low. This low variation is primarily due to the fact that the sample is from only three different regions in Sweden. Adding to this is the problem that observations are available for only one year. A series of observations over time is likely

⁴⁷ 100 öre = 1 SEK = 0.13 US \$, October 3, 1997.

to have increased the observed variation in electricity price. The prices used are the marginal prices and the data source is Svenska Elverksföreningen (1987 and 1988). In this table another variable that is likely to influence the demand for electricity is present, namely the number of persons that the household consists of. The observations of single family households electricity consumption shows a high level of variation. This variable is the dependent variable in the regression equations in section 6.3.

Table 6.5 Other Variables, Multi Family Housing

Variable	Mean	Standard Deviation
ELPRICE (öre/kWh)	0.371	0.016
ELCONS (kWh/year)	2,813.0	4,744.0
INCOME (SEK 1986)	100,319.0	56,331.0
ELHEAT	0.001	0.025
NUMBER (Persons/HH)	1.661	0.888

The issue of lack of variations in the electricity price is obvious in the case of multi family households as well. The reasons behind the problem are the same as for single family households and given the sample nothing can be done but to use the existing data. Variations are present in the income and number of persons per household variables, even though they are lower than for the single family housings.

6.2.2.2 Correlations in the material

Information about the material can be extracted by examining correlations between the different variables. The correlation discussed in this section is the simple correlation between two variables. From this it is possible to find out to what extent pairs of variables vary together. What the correlation coefficients do not include information about is how the causality relations between the variables are linked. It is possible to conclude to what extent two variables fluctuate together, but not which one of them that influences the other. These simple correlation coefficients could nevertheless be helpful tools in the process of deciding how to formulate and which variables to include in a regression equation intended to explain the variations in electricity demand. This implies that to find interesting candidates for the regression equation focus is aimed at locating variables that have a high degree of correlation primarily with electricity consumption. The complete discussion is carried out in Appendix

6.B where the corresponding tables are displayed as well. The main conclusion of the discussion is that it is vital to separate the single family households into two separate groups depending on whether they have direct electrical heating or not. If this is not done the magnitude of the price effect is likely to be over emphasized in the estimations to follow.

6.3 Electricity demand model

6.3.1 Hypotheses concerning factors of electricity demand

How can a model be constructed to capture the different aspects of electricity demand? By studying the information given by the variations and the correlations in the data material potential candidates have been chosen concerning which variables to include in a regression equation for estimations of electricity demand. A model should then be formulated in order to answer questions and hypotheses raised by economic theory. In the process of modeling the demand for electricity, we will try to find answers to the following proposed hypotheses concerning the knowledge we have about the households and their demand for electricity.

1. The household income has a positive influence on electricity demand.
2. The electricity price has a negative influence on electricity demand.
3. The size of living area has a positive influence on electricity demand.
4. The number of household members has a positive influence on electricity demand.
5. The local weather characteristics have a positive influence on the demand for electricity; the colder it is, the more electricity is used.
6. The composition and saturation level of electrical appliances are important; each appliance has a positive influence on electricity demand.

6.3.2 Specification of regression model

For each individual household i the electricity demand E_i can be seen as a function of the stock of electrical appliances possessed by the household plus a function of other household

related variables as discussed in the introduction. Following equation (1) this can be written:

$$E_i = \beta_0 + \beta_1 A_i + \beta_2 B_i + \beta_3 Y_i + \beta_4 P_i + \beta_5 Z_i + \varepsilon_i \quad (5)$$

where A_i is the vector of dummy variables for the households electrical appliances and B_i is the vector of variables for household members' behavior, such as average temperatures kept in different rooms. Y_i is the variable for household income, and P_i is the variable for electricity price. Z_i is the vector of variables that represent other household characteristics, such as number of household members, size of dwelling, and heating degree days. The ε_i is an error term. The coefficients for the different variables are represented by β_j . Specified like this the coefficients β_3 and β_4 capture only the direct influence from household income and electricity price. The indirect influence from income and electricity price through household appliances and behavior, as described in equation (2) and (3), can be written as:

$$A_i = \alpha_0 + \alpha_1 Y_i + \alpha_2 P_i + u_i \quad (6)$$

and

$$B_i = \gamma_0 + \gamma_1 Y_i + \gamma_2 P_i + v_i. \quad (7)$$

Substitute equations (6) and (7) into equation (5) in order to get

$$E_i = \beta_0 + \beta_1 A_i^* + \beta_2 B_i^* + \beta_3 Y_i + \beta_4 P_i + \beta_5 Z_i + \varepsilon_i \quad (8)$$

where A_i^* and B_i^* represent the expressions in equations (6) and (7). This can be rearranged in the following way:

$$E_i = \beta_0 + (\beta_1 \alpha_1 + \beta_2 \gamma_1 + \beta_3) Y_i + (\beta_1 \alpha_2 + \beta_2 \gamma_2 + \beta_4) P_i + \beta_5 Z_i + \varepsilon_i. \quad (9)$$

By defining $N = (\beta_1 \alpha_1 + \beta_2 \gamma_1 + \beta_3)$ and $K = (\beta_1 \alpha_2 + \beta_2 \gamma_2 + \beta_4)$ equation (9) can be rewritten as

$$E_i = \beta_0 + N Y_i + K P_i + \beta_5 Z_i + \varepsilon_i. \quad (10)$$

Specified like this the coefficients N in front of Y_i and K in front of P_i capture the combined effect from the direct and indirect influences of income and electricity price on electricity demand. In equation (10) the influences through the household's stock of appliances and household specific behavior can not be identified separately, instead the specification allows

us to estimate the total price and income effect on electricity demand. The first set of estimations carried out will follow the specifications in equation (10).

In order to use the information contained in the appliance dummy variables and the variables for consumer behavior the second set of estimations will be carried out following the specifications in equation (5). Following this specification only the direct influence of price and income will be captured, but together these two estimations will enable us to discuss all of the proposed hypotheses above.

A problem with these specifications is that they do not take into account the interaction that is present between the electric heating and appliances such as refrigerator and dryer. Since the refrigerator and the dryer produce heat for the surroundings when they are operated the need for heat from the electric heating system is reduced. This effect is not included in the regression equations since no information about the magnitude of this effect is available in the data.

6.3.3 Choice of functional form

In the previous section the functions have been specified as linear. This specification does not necessarily have to be the ideal one. The choice of functional form can be viewed as an empirical question, and the object when choosing functional form is to find and use the one that best fits the data. Particular forms considered initially were the linear, the semi-log, and the log-linear functional form. These two latter functional forms are however only transformations of data, forming special cases of the more general Box-Cox transformation. Since the object stated above is to find the best fitting functional form it appears sensible to use this more general form in order to find the most suitable transformation of data. The Box-Cox transformation of variable y is given by

$$y^\lambda = \begin{cases} (y^\lambda - 1)/\lambda & \lambda \neq 0 \\ \ln y & \lambda = 0 \end{cases} \quad (11)$$

In the most general case this transformation is carried out on each variable included in the model, using the optimal λ for each variable. If the model contains a large amount of variables the search for optimal transformation parameters can be rather tedious. Generality is on the other hand lost if only one variable is transformed. A compromise is to use one transformation parameter for the dependent variable and another parameter for the group of independent

variables. The latter method is followed in this study. The dependent variable is transformed by one parameter θ , and each independent variable, except the constant term and the dummy variables, are transformed by another parameter λ . This can be written:

$$y^\theta = \beta x^\lambda + \gamma a \quad (12)$$

where x is a vector of the independent variables subject to transformation and a is a vector of the independent variables that are not transformed.

To find optimal values of λ and θ , i.e. the values that imply the best fitting functional form, maximum likelihood estimations were used to obtain parameters that maximized the following log-likelihood function:

$$L_{\max}(\theta, \lambda) = -\frac{1}{2} N \ln \sigma_e^2(\theta, \lambda) + (\theta - 1) \sum_{i=1}^N \ln y_i \quad (13)$$

where σ_e^2 is the error variance and N is the number of observations.

These estimations were first carried out following the specifications in equation (10). One separate estimation for single family housing, with and without electric heating, and one for multi family housing. For the three different observation groups the values of θ and λ displayed in Table 6.6 were found to be optimal.

Table 6.6 Estimated transformation parameters for specifications following equation (10)

Type of housing	θ	λ	Log-likelihood
Single family Electric heating	0.54773* (20.00)	0.11425* (1.90)	-10,175.93
Single family No electric heating	0.52988* (7.56)	0.08980* (1.82)	-8,611.20
Multi family	-0.14375* (-6.85)	0.53859* (4.02)	-3,808.47

T-values in parentheses

* Significant at the 0.05 level

Significant at the 0.10 level

Before continuing we would like to establish whether the estimations using these transformations are significantly different from estimations using θ and λ that would turn the estimated equations into commonly used specifications, such as linear, semi-log, and log-linear functional forms. In Appendix 6.C it is shown that the latter three functional forms can be rejected for each group of housing, and the choice is therefore made to use the parameters above in the estimations. Another fact supporting this is the observed significance level of the transformation variables θ and λ in the three different cases that are estimated.

The same procedure is then repeated following the specifications in equation (5). In comparison to equation (10) this implies the addition of household specific information, in the form of appliance dummy variables and variables indicating household specific behavior. The decision concerning which variables to include follow the conclusions drawn in section 6.2. The values of θ and λ displayed in Table 6.7 were found to maximize the log-likelihood function for each group of housing.

Table 6.7 Estimated transformation parameters for specifications following equation (5)

Type of housing	θ	λ	Log-likelihood
Single family Electric heating	0.60762* (19.41)	0.12507* (1.89)	-10,050.58
Single family No electric heating	0.52498* (7.79)	0.07182* (1.79)	-8,255.14
Multi family	-0.11870* (-4.68)	0.56104* (3.75)	-3,723.33

T-values in parentheses

* Significant at the 0.05 level

* Significant at the 0.10 level

A comparison between the values of θ and λ representing the linear, semi-log, and the log-linear functional forms is shown in Appendix 6.C. The conclusion is the same as in the previous case; all three alternative functional forms can be rejected. The search for optimal functional form can then be terminated and the discussion can instead turn to the estimation results.

6.3.4 Estimation results

The estimations of the demand equations are carried out in the same order as during the search for the optimal functional form: First the total price and income effects are estimated for the three groups following the specifications in equation (10). Then the direct price and income effects are estimated separately from the indirect effects, which instead are carried through each household's appliance stock and behavioral pattern, following the specifications in equation (5).

6.3.4.1 Estimations of total price and income effects

Box-Cox estimations were made using the transformation parameters in Table 6.6. For single family housing with direct electric heating the price coefficient had a negative sign and the income coefficient had a positive sign. The price coefficient was significant at the 5% level, and the income coefficient was significant at the 10% level. These results fit the hypotheses above about a negative price effect and a positive income effect. For single family housing without electric heating and for multi family housing the estimated price and income coefficients were insignificant. These findings are not surprising. The coefficient for living area had a positive and significant sign for both groups, implying that one very important factor behind the demand for electricity for these groups is the size of the home. Based on the observation that the estimated price and income coefficients were insignificant for single family housing without electric heating and for multi family housing, the decision is made to exclude these groups from the discussion in the next section. Price and income elasticities were calculated at the mean of the price and the income variables using the estimated regression coefficients, and the results are shown in Table 6.8.

Table 6.8 Estimated price and income elasticities

Type of housing	Price elasticity	Income elasticity
Single family Electric heating	-1.37*	0.07 [#]
Single family No electric heating	-0.64	0.50
Multi family	-1.38	-0.001

* Significant at the 0.05 level

[#] Significant at the 0.10 level

The long run price elasticity was -1.37 and the income elasticity 0.07 for single family housing with electric heating. This price elasticity is high compared to the results from two other similar studies: Morss & Small (1989) found an estimated price elasticity of -0.38, Parti & Parti (1980) found a price elasticity of -0.58. However, Eitheim et. al. (1989) estimated a price elasticity of -1.21, which is much closer to the results obtained here. It is important at this stage to note that electricity prices are perfectly correlated with the geographical regions and will therefore include every site specific factor that is not specified explicitly elsewhere. The price elasticity is the total effect from the price influence, as defined in equation (10). One would expect that the direct price effect estimated in the next section will be somewhat lower.

6.3.4.2 Estimations of direct price and income effects

Based on the decision made in the previous section only the results for single family housing with electric heating is discussed here. The estimation was made using the transformation parameters for θ and λ in Table 6.7, and the estimated parameters for the demand equations are shown in Table 6.A.1 (Single Family Housing with Electric Central Heating) in Appendix 6.A. By using this specification of the regression model, much information contained in the appliance dummy variables and the behavioral variables has been added. This has increased the precision in the regression which can be seen by conducting a chi-square test following the same procedure as in Appendix 6.B. The value of the log-likelihood function from this equation (equal to -10,050.58) is outside the 95% confidence interval for the value of the log-likelihood function for the equation estimated previously (which was equal to -10,175.93).

Regarding the estimated parameters for the appliance dummy variables there is no convincing pattern that can bring an answer to the last hypothesis stated above; some of them are positive while others have a negative sign, and some are significant and others are not. The coefficients for measures to conserve electricity also have a mixture of positive and negative signs, but only one is significant. A negative sign shows that there is a negative relationship between measures taken to reduce energy use and actual electricity consumption. A positive sign indicates that residents in houses with a high level of electricity consumption are more likely to invest in energy conserving measures. The variable heating degree days is significant but has a negative sign. This result could be due to the possibility that when expectations of cold weather are high the houses are adapted accordingly when they are built, and as a result those houses use less electricity for heating, even though they are situated further north. As would be expected a larger home implies a higher demand for electricity as can be seen

through the variable living area's positive sign. The variable for construction year has a negative coefficient and that can be interpreted as follows; a more recently built house uses less electricity to provide the same level of comfort as an older house. This effect can be strong enough to produce a significant coefficient. The behavioral factors covered by temperatures maintained in different rooms are insignificant and have a mix of positive and negative signs.

The direct income effect is positive, but the coefficient is not significant. The coefficient for electricity price has the expected negative sign and it is significant. From the estimated coefficients elasticities can be calculated, and the results are shown in Table 6.9.

Table 6.9 Estimated price and income elasticities

Type of housing	Price elasticity	Income elasticity
Single family		
Electric heating	-1.26*	0.07

* Significant at the 0.05 level

Significant at the 0.10 level

The long run income elasticity is calculated to be 0.07, and the long run price elasticity to -1.26. This result is not much lower than the total elasticity calculated in the previous section. One conclusion is that the indirect price effect carried through the appliance variables added to the equation in this estimation is not very large. It is possible that a large part of the total price effect comes from household specific behavior and since only a few variables of this type were added the coefficient for the price variable did therefor not change much.

Another aspect to return to is the consequences of perfect correlation between the electricity price and the geographical region. The price variable then presumably includes all site specific information not included elsewhere in the equation and this may in turn lead to bias of the estimated coefficient. It is however difficult to envision a number of factors to be added that is not already included among the independent variables. It is possible that depending on where people live they have adapted different attitudes towards electricity use. People in the northern parts of Sweden live close to hydro power stations and some have perhaps been living under the notion that electricity is easily accessible and also inexpensive. This way of thinking could induce them to use more electricity, and if this type of preference is specific to a certain region

it is an example of a site specific factor that is not included among the variables, and that could help explain the high estimated price elasticity.

The explanatory power of the independent variables taken altogether is represented by the adjusted R^2 , and it is found to be 25% in this case. This shows that even though we have access to all this detailed information about individual households, it is only possible to explain a quarter of the variations in individual households electricity consumption. However, it is important to point out that the data used is cross-sectional and it is not self-evident that the R^2 is the best measure to judge the regression by. The regression taken as a whole can be tested by an F-test, and by that it is found that the regression coefficients together are significant at the 0.05 level. (See Table 6.A.1 in Appendix 6.A). The explanatory power could be increased by the addition of more information about how consumers behave and what kind of preferences they have. Perhaps some people regulate the temperature inside by opening the windows. Other information that could improve these results is observations on the composition of the household members; age structure and education level of household members could be important factors behind different behavioral patterns that affect the households electricity consumption. It is however most likely that the best way to improve the explanatory power of the regression is the use of panel data that combine time-series and cross-sectional data, instead of only cross-sectional.

6.4 Concluding remarks

The purpose of this paper has been to estimate the residential demand for electricity in Sweden using a large database consisting of individual household data. The estimation results suggest two important conclusions:

1. The price of electricity is an important explanatory variable.
2. Even though much information about households is used, only a very small share of the individual households variations in electricity consumption can be explained.

First, the estimated price elasticity is high, which could be caused by reasons discussed earlier. The long run price elasticity estimated here does not indicate much about the short run effects of price changes, and could be consistent with very low short run price elasticities. The critical point is that the results indicate that the price of electricity plays a significant role in determining residential electricity demand.

Second, the explanatory power of the estimated regression equations was found to be low. This means, even though it is not a perfect measure for the precision of the regression equation, that even though we have access to all this detailed information it is not possible to explain more than 25% of the individual households variations in residential electricity consumption.

In order for further research to bear fruit, more and different data may be an important factor. In that case more information concerning the households socio-economic factors would be essential; more information about how individuals behave and react to energy related issues, i.e., information about preferences and habits. In addition to this type of data it is essential to be able to combine time-series with cross-sectional data in order to improve the precision in the regressions. Then we might be able to say something more about how future electricity demand will develop.

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Appendix 6.A - Demand equation parameter estimates

Table 6.A.1 Demand Equation Parameter Estimates,
Single Family Housing with Electric Central Heating

Variable	Parameter Estimate	T-Ratio
INTERCEPT	1314.60*	3.15
FREEZER2	8.52	0.92
DISHWASH	7.89	0.75
WATER HEAT	-50.52*	-2.17
SAUNA	-3.64	-0.38
TUMBLE	-48.97*	-2.31
DRYER	-85.87*	-2.92
CARHEAT	-5.27	-0.41
INSULATION	26.61*	1.96
DOORLIST	-9.47	-1.10
INSULROOF	13.05	0.98
HDD	-25.17*	-1.98
NUMBER	20.04	1.77
AREA	109.69*	1.97
CONSTR YEAR	-13.22*	-2.56
LIVINGRMTEMP	-68.19	-1.17
BEDRMTEMP	23.97	0.58
KITCHENTEMP	94.68	1.37
INCOME	18.46	1.40
ELPRICE	-817.98*	-2.08

* Significant at the 0.05 level

Adjusted R²: 0.25

Number of observations: 957

$F_{20,957} = 20.56 > F_{(\alpha=0.01)} = 1.88$

Appendix 6.B - Correlation coefficients

In section 6.2.2.1 a first description of the data was carried out and some conclusions were made regarding which variables to include in the regression equations. Here the object is to further discuss information about the data in order to spot interesting candidates for the regression equations. In the earlier section the appliances stove, refrigerator, freezer number one, kitchen fan, and washing machine were concluded to be present in almost every single family household and were therefore suggested to be dropped as individual independent variables in the regression equations. Two variables, freezer number three and infra heat, had too low saturation levels to be considered as interesting. We can from this table conclude that they also have low levels of correlation with the electricity consumption, and the decision to exclude them seems therefore correct. For the remaining variables we are interested in the ones that have a high correlation with primarily electricity consumption since this is the dependent variable in the regression equations. Freezer number two, dishwasher, water heater, dryer, sauna, and car heater, all have correlations that are high enough to indicate that they can contribute to explain the observed variations in electricity consumption. The low correlation between electricity consumption and tumble dryer indicates that the latter will not contribute very much in the regression runs, and it will thus be excluded.

Table 6.B.1 Correlation Coefficients, Single Family Housing

Variables	ELCONS	ELPRICE	INCOME
STOVE	0.038	-0.027	0.029
FRIDGE	0.016	-0.006	0.005
FREEZER	0.063	-0.008	0.112
FREEZER2	0.168	-0.056	0.181
FREEZER3	0.044	0.081	0.089
FAN	0.041	-0.044	0.105
DISHWASH	0.293	-0.198	0.352
WATERHEAT	0.301	-0.499	0.168
WASHER	0.315	0.248	0.243
DRYER	0.115	-0.383	0.138
TUMBLE	0.031	0.015	0.128
INFRA	0.015	0.032	0.074
SAUNA	0.309	-0.223	0.314
CARHEAT	0.333	-0.361	0.295
ELHEAT	0.455	-0.965	0.137

The variable electric heat has an almost perfect negative correlation with electricity price, and has a high positive correlation with electricity consumption. At a quick glance this seems to support economic theory that if electricity prices are low consumers choose electric heat in their homes and the electricity consumption is accordingly high. But we know that in the case of electric heating the chain of events work in another direction; the consumer chooses a home given her preferences and budget constraint, the home is equipped with a certain heating type, if the heating is direct electric the home has been placed in a different tariff structure with considerable lower electricity prices than what a comparable household without electric heating would face. In other words, the consumer does not choose the electric heat because she faces a low electricity price, she gets the low price as a result of the already installed electric heat. One important conclusion from this is that in the upcoming regressions it is vital to separate households with electric heat and households without in order not to over-emphasize the importance of electricity price on electricity consumption.

Table 6.B.2 Correlation Coefficients, Multi Family Housing

Variables	ELCONS	ELPRICE	INCOME
STOVE	0.023	0.024	0.049
FRIDGE	0.004	0.023	-0.009
FREEZER	0.136	-0.157	0.126
FREEZER2	0.178	0.001	0.136
FREEZER3	0.179	-0.013	0.076
FAN	0.154	-0.039	0.114
DISHWASH	0.245	-0.059	0.251
WATERHEAT	0.402	0.017	0.038
WASHER	0.221	-0.051	0.189
DRYER	0.106	0.032	0.035
TUMBLE	0.121	-0.001	0.077
INFRA	0.155	0.011	0.043
SAUNA	0.289	-0.047	0.106
CARHEAT	0.105	-0.393	0.385
ELHEAT	0.151	-0.023	0.035

For multi family households only the stove and refrigerator were found to be present in almost every household and were therefore suggested to be dropped, according to the conclusions in section 6.2.2.1. Another judgment from that section concerns the variables that are present in so few households that they will not be included at all in the regression equation. The variables are; dishwasher, water heater, washing machine, tumble dryer, infra heat, sauna, and electric heat. Even though several of them show a relatively high degree of correlation with the electricity consumption, their occurrence is so rare that the decision to exclude them is

retained. This also concerns the problem with electric heat that was apparent for single family households, but in this case the occurrence of it is so infrequent that no distinction has to be made between households with or without electric heat. The remaining variables indicate that they can be useful in the regression equations.

Table 6.B.3 Correlation Coefficients, Single Family Housing

Variables	ELCONS	ELPRICE	INCOME	ELHEAT
AREA	0.298	-0.106	0.306	0.087
NUMBER	0.094	-0.112	0.285	0.111
HDD	0.169	-0.252	0.082	0.128
LIVINGRMTEMP	-0.093	0.034	-0.026	-0.041
BEDRMTEMP	-0.127	0.076	-0.087	-0.072
KITCHENTEMP	-0.121	0.081	-0.023	-0.076

In this table some household specific characteristics other than electric appliances are displayed. As earlier high correlations with primarily electricity consumption are sought after. Household area, number of persons per household, the geographical variable heating degree days all seem to vary together with electricity consumption and will therefore be candidates for inclusion in the regression equation. The more socio-economic factors concerning average temperatures kept in different rooms are all negatively correlated with electricity consumption, which appears somewhat surprising, but they are still interesting as representations of household members behavior.

Table 6.B.4 Correlation Coefficients, Multi Family Housing

Variables	ELCONS	ELPRICE	INCOME	ELHEAT
AREA	0.357	-0.033	0.353	-
NUMBER	0.173	-0.055	0.491	0.038
HDD	-0.199	-0.504	0.065	0.021
LIVINGRMTEMP	-0.054	0.051	-0.018	-0.011
BEDRMTEMP	-0.049	0.111	-0.069	0.011
KITCHENTEMP	0.013	0.071	0.021	-0.023

For these variables the same observations are made for the multi family households as in the single family case. Household area, number of persons, and heating degree days are judged in

favor as potential candidates for inclusion in the regression equation. The correlations between the different room temperatures and electricity consumption is not very high, but as argued for single family households, it is interesting to include variables that reflect specific household behavior.

Table 6.B.5 Correlation Coefficients, Single Family Housing

Variables	ELCONS	ELPRICE	INCOME	HDD
INSULATION	0.141	-0.141	0.082	-0.042
DOORLIST	0.125	0.013	0.037	0.045
SEALED	0.022	0.026	0.058	-0.035
INSULWALL	-0.044	0.158	-0.112	-0.061
INSULROOF	-0.040	0.131	-0.058	-0.071
THREEGLASS	0.015	-0.051	0.085	0.104
WOODFURNACE	0.032	-0.079	0.102	0.057
GROUND INSULATED	-0.023	-0.004	0.001	-0.051

The conclusion from the saturation levels of these variables was that additional insulation, added door lists, and insulated roof were potentially interesting for the regression equations. It is difficult to see evidence of anything that would change that conclusion among these correlation coefficients. They are all rather low and have no consistency among the signs and it is therefore no reason to change the set chosen in the previous section.

Appendix 6.C - Comparison of functional forms

Comparison of functional forms in order to establish whether the values of θ and λ that maximizes the log-likelihood function (L_{\max}) are significantly different from the values of θ and λ that implies the linear, the semi-log, and the log-linear functional form. A confidence region for θ and λ is described by Zarembka (1987). For a 95 % confidence interval, the region can be obtained from :

$$L_{\max}(\theta^*, \lambda^*) - L_{\max}(\theta', \lambda') < \frac{1}{2} \chi^2(0.05) \quad (C1)$$

where $1/2 * \chi^2$ for a 0.05 level of significance and 2 degrees of freedom is equal to $1/2 * 5.991 = 2.9955$

6.C.1 First set of estimations; following the specifications in equation (10)

By using the definition above, the following comparison between the values of the log-likelihood function for the different functional forms can be carried out:

1. Single family housing with electric central heating

Maximizing $\theta = 0.54773$, and $\lambda = 0.11425$

Value of log-likelihood function = -10 175.93

Linear: $L_{\max}(1,1) = -10\,205.40$ and $-10\,175.93 - (-10\,205.40) = 29.47 > 2.9955$

Semi-log: $L_{\max}(0,1) = -10\,390.71$ and $-10\,175.93 - (-10\,390.71) = 214.78 > 2.9955$

Log-linear: $L_{\max}(0,0) = -10\,398.04$ and $-10\,175.93 - (-10\,398.04) = 222.11 > 2.9955$

2. Single family housing without electric central heating

Maximizing $\theta = 0.52988$, and $\lambda = 0.08980$

Value of log-likelihood function = -8 611.20

Linear: $L_{\max}(1,1) = -8\,698.32$ and $-8\,611.20 - (-8\,698.32) = 87.12 > 2.9955$

Semi-log: $L_{\max}(0,1) = -8\,687.43$ and $-8\,611.20 - (-8\,687.43) = 76.23 > 2.9955$

Log-linear: $L_{\max}(0,0) = -8\,685.45$ and $-8\,611.20 - (-8\,685.45) = 74.25 > 2.9955$

3. Multi family housing

Maximizing $\theta = -0.14375$, and $\lambda = 0.53859$

Value of log-likelihood function = -3 808.47

Linear: $L_{\max}(1,1) = -4\,229.74$ and $-3\,808.47 - (-4\,229.74) = 421.27 > 2.9955$

Semi-log: $L_{\max}(0,1) = -3\,821.06$ and $-3\,808.47 - (-3\,821.06) = 12.59 > 2.9955$

Log-linear: $L_{\max}(0,0) = -3\,819.71$ and $-3\,808.47 - (-3\,819.71) = 11.24 > 2.9955$

As can be seen, neither the linear, the semi-log, or the log-linear functional form, is included in the confidence region for any of the groups.

6.C.2 Second set of estimations; following the specifications in equation (5)

1. Single family housing with electric central heating

Maximizing $\theta = 0.60762$, and $\lambda = 0.12507$

Value of log-likelihood function = -10 050.58

Linear: $L_{\max}(1,1) = -10\,083.13$ and $-10\,050.58 - (-10\,083.13) = 32.55 > 2.9955$

Semi-log: $L_{\max}(0,1) = -10\,305.31$ and $-10\,050.58 - (-10\,305.31) = 254.73 > 2.9955$

Log-linear: $L_{\max}(0,0) = -10\,306.74$ and $-10\,050.58 - (-10\,306.74) = 256.16 > 2.9955$

2. Single family housing without electric central heating

Maximizing $\theta = 0.52498$, and $\lambda = 0.07182$

Value of log-likelihood function = -8 255.14

Linear: $L_{\max}(1,1) = -8\,325.99$ and $-8\,255.14 - (-8\,325.99) = 70.85 > 2.9955$

Semi-log: $L_{\max}(0,1) = -8\,341.19$ and $-8\,255.14 - (-8\,341.19) = 86.05 > 2.9955$

Log-linear: $L_{\max}(0,0) = -8\,342.12$ and $-8\,255.14 - (-8\,342.12) = 86.98 > 2.9955$

3. Multi family housing

Maximizing $\theta = -0.11870$, and $\lambda = 0.56104$

Value of log-likelihood function = -3 723.33

Linear: $L_{\max}(1,1) = -4\ 150.32$ and $-3\ 723.33 - (-4\ 150.32) = 426.99 > 2.9955$

Semi-log: $L_{\max}(0,1) = -3\ 732.24$ and $-3\ 723.33 - (-3\ 732.24) = 8.91 > 2.9955$

Log-linear: $L_{\max}(0,0) = -3\ 731.91$ and $-3\ 723.33 - (-3\ 731.91) = 8.58 > 2.9955$

As in the previous case, neither the linear, the semi-log, or the log-linear functional form, is included in the confidence region for any of the housing groups. The conclusion is that the three functional forms, linear, semi-log, and log-linear, can be rejected for both sets of estimations.

Appendix 6.D - Variables in the data base

1. TOWN: Kalix, Vännäs or Tierp
2. SELECTION: Single family or multi family housing
3. HOUSHM: Members of household, adults and children
4. AGEWOMAN: Age of woman
5. AGEMAM: Age of man
6. INCWOMAN: Income of woman
7. INCMAN: Income of man
8. FLOORS: Number of floors in one family housing
9. OWNER: Type of ownership
10. HEAT IN RENT: Cost for heating included in the rent
11. AREA: Living area
12. GARAGEHEAT: Heated garage
13. ROOM: Number of rooms
14. HEAT: Type of space heating; electricity, oil etc.
15. INSULATION: Well insulated house
16. WINDLIST: Insulated windows
17. DOORLIST: Insulated doors
18. SEALED: Sealed house
19. INSULWALL: Increased insulation in walls
20. INSULROOF: Increased insulation in roof
21. THREEGLASS: Changed to three-glass windows
22. WOODFURNACE: Installed wood-furnace
23. CHANGED HEATER: Changed heating system
24. GROUND INSULATED: Ground insulation
25. OTHER: Other energy preserving measure
26. EL IN RENT: Electricity included in rent
27. STOVE: Electric stove
28. FRIDGE: Refrigerator
29. FREEZER: Freezer number 1
30. FREEZER2: Freezer number 2
31. FREEZER3: Freezer number 3
32. FAN: Kitchen fan
33. DISHWASH: Dishwasher
34. WATERHEAT: Electric water heater

- 35. WASHER: Washing machine
- 36. DRYER: Electric clothes dryer
- 37. TUMBLE: Tumble dryer
- 38. INFRA: Infra heat
- 39. SAUNA: Electric sauna
- 40. RADIATOR: Extra electric radiator
- 41. CARHEAT: Heater for car
- 42. ENGHEAT: Heater for car engine
- 43. LIVINGRMTEMP: Temperature in living room
- 44. BEDRMTEMP: Temperature in bedroom
- 45. KITCHENTEMP: Temperature in kitchen
- 46. GARAGETEMP: Temperature in garage
- 47. NIGHTDAY: Same temperature day and night
- 48. TEMPDIFF: Different temperature in different rooms
- 49. LIGHTS: Number of lights
- 50. LIGHTSON: Number of lights on
- 51. FRFREEZ: Frost free freezer
- 52. CONSTR YEAR: Construction year of house
- 53. ELCONS: Consumption of electricity, kWh/year.
- 54. WATERCONS: Consumption of water, cubic meters/year.
- 55. ELPRICE: Price of electricity, öre/kWh.
- 56. HDD: Heating degree days
- 57. INCOME: Income of household, 1986 SEK
- 58. ELHEAT: Electric space heating
- 59. NUMBER: Number of persons in household

Chapter 7

A Search Cost Approach to Energy Efficiency Barriers

7.1 Introduction

Several studies suggest (see for example Johansson et al. (1989)) the existence of significant possibilities to reduce energy use by the implementation of technologies that are cost effective under today's economic conditions, but are still not fully exploited. Ruderman et al. (1984) conducted a study of consumer purchases of residential appliances and heating and cooling equipment. They found that consumers could achieve considerable present-value savings by changing from the models actually purchased to more energy efficient alternatives.

This apparent anomaly between the suggested opportunities to conserve energy cost-effectively and the empirical findings that those opportunities are yet not fully exploited, can be interpreted in two different ways. One is that there are irrational barriers to the implementation of cost-effective measures to energy conservation, i.e. the consumers have access to the relevant information but are still making purchase decisions that are not cost-effective. The other is that the agents behave economically rational, but that they take into account additional factors when making the purchase decision than what is included in prevalent technology-economic studies of measures to energy conservation.

Several factors have been suggested to explain this "efficiency gap". They have been described mainly in terms of problems related to consumer decision-making (see for example Carlsmith, et al. (1990)). One of the first issues that comes to mind is that consumers lack full information concerning the performance of energy-efficient technology. Numerous other factors have been discussed in the literature: Uncertainty on behalf of the consumers concerning future economic conditions and the performance of the energy using equipment (Sutherland (1991)), credit rationing (supported by Hausman's findings (1979)), principal-agent problems (Fischer and Rothkopf (1989)), and the argument that consumers' perceptions regarding product performance may distort the market's adaptation of energy-efficient technology (Howarth and Andersson (1993)).

No single factor of the ones listed above appear to explain the problem completely, which in turn supports the idea that some additional factor has to be considered in order to better understand the issue. Several of the issues brought forward are associated with uncertainty and consumers' access to information. The main argument in this paper is based on the notion that one important factor yet to be included in the discussions of an efficiency gap is the cost associated with the consumer's search for relevant information. If this search could be undertaken costlessly this would not be a significant problem, but in order to carry out the search the individual consumer has to invest time, time that has to be taken from the total amount of time at his/her disposal. The idea of time being of limited disposal to the household members has been discussed by for example Burenstam Linder (1970), as well as in most models of labor supply. One important point is that the consumers in a household are constantly struggling in order to allocate time to the tasks where they find it most useful. This implies, according to economic theory and in the case of energy-efficient technology, that the consumer will at the margin equate the marginal cost of an extra hour spent on search for the best purchase to the marginal benefit of an extra hour spent on the search.

The purpose of this chapter is to show that the existence of a search cost could induce a rational consumer to chose energy using equipment that would not be selected if the consumer had been well-informed at the beginning of the search process. The focus of the chapter is restricted to the discussion of purchase decisions taken by consumers that have made the decision to purchase new equipment. For a discussion regarding investment decisions under uncertainty about new, and better performing, equipment available some time in the future, and the option value of waiting for this, see for example Pindyck (1991). In this study no attention is paid to the optimal point in time when replacement of an existing model should be made. The chapter is organized in the following way: Section 7.2 contains a description of the

search cost model. In section 7.3 a numerical example is shown, and in section 7.4 some concluding remarks are made.

7.2 A search cost model

The basic notion behind the model is that the consumer will shop for a better bargain as long as the expected marginal benefit of sampling one more appliance model or store exceeds the cost of shopping. It is important to immediately point out that a one-to-one relationship between the cost-effectiveness and the energy-efficiency of different models is assumed here. This implies that models representing a lower present value of purchase price and energy cost are the more energy-efficient models, and vice versa. This assumption is reasonable to make following the observations made in the empirical studies mentioned above.

The objective for the agent is to derive a strategy to minimize the expected value of the random variable "price of appliance plus total costs of search". Presumably the minimization will involve a sequential strategy where the agent inspects each draw and, depending on its value, decides whether to continue the search or not. Denote each offer x found on the market to reflect the present value of the total cost associated with the purchase, i.e. $x = p + e$, where p is the purchase price of the appliance, and e is the present value of the expected cost for energy used by the appliance, discounted over the life-cycle of the appliance. Each offer reflects not only the purchase price, which is easily observed in the store, but is a measure of the total cost associated with the purchase of one specific appliance. The agent selects independent drawings of appliances from a distribution F .⁴⁸ Each drawing is associated with a cost c consisting of two parts: the time needed to locate each offer and the time and effort to estimate the energy cost that is associated with the offer, as defined above.

Consider then the problem of an agent that has found offer x' . Let the function $v(x')$ be the minimum expected cost for the appliance for an agent who has offer x' in hand. The definition of this function can be described in the following way: The agent can either accept the offer x' in hand and terminate the search; or reject the offer, bear an additional search cost, and find a new offer. For this problem the Bellman equation, as stated similarly by Sargent (1987), can

⁴⁸ Consider $F(X)$ as a cumulative probability distribution function of a random variable x defined by $\text{prob}(x \leq X) = F(X)$. Assume that $F(0)=0$, i.e. x is nonnegative. Another condition is that $F(\infty)=1$.

be written

$$v(x') = \min \left\{ x', c + \int_0^{\infty} v(x) dF(x) \right\}. \quad (1)$$

The second expression in (1) is a positive constant, and there must exist a critical number x^* , such that the optimal strategy for the agent is to accept offers $x \leq x^*$ and to reject offers $x > x^*$. Thus, the agent sets a reservation price equal to x^* , which can be written in terms of F and c

$$x^* = c + \int_0^{\infty} v(x) dF(x) \quad (2)$$

and this can be written as

$$x^* = c + \int_0^{x^*} x dF(x) + x^* \int_{x^*}^{\infty} dF(x) \quad (3)$$

or

$$x^* \int_0^{x^*} dF(x) + x^* \int_{x^*}^{\infty} dF(x) = c + \int_0^{x^*} x dF(x) + x^* \int_{x^*}^{\infty} dF(x). \quad (4)$$

This can be rearranged in the following way

$$\int_0^{x^*} (x^* - x) dF(x) = c. \quad (5)$$

Then use the integration-by-parts formula $\int u dv = uv - \int v du$ and define $u = (x^* - x)$ and $dv = dF(x)$ in order to get

$$\int_0^{x^*} (x^* - x) dF(x) = \int_0^{x^*} F(x) dx. \quad (6)$$

This can then be substituted into equation (5) in order to get the following expression:

$$\int_0^{x^*} F(x) dx = c. \quad (7)$$

From this it is clear that a relationship exists between the search cost c and the reservation price x^* . In order to analyze this relationship further the following function can be defined, as suggested by Sargent (1987),

$$g(x) = \int_0^x F(s) ds. \quad (8)$$

This function describes the expected gain from continued search, and is assumed to have the following characteristics: $g(0)=0$, $g(x) \geq 0$, $g'(x)=F(x) > 0$, and $g''(x)=F'(x) > 0$ for $x > 0$. The optimal rule, as stated before, is then to search again when the additional cost of a search is less than the expected gain from that search, i.e. accept $x \leq x^*$, reject $x > x^*$, and x^* must satisfy $g(x^*)=c$. This relationship can be portrayed as in Figure 7.1.

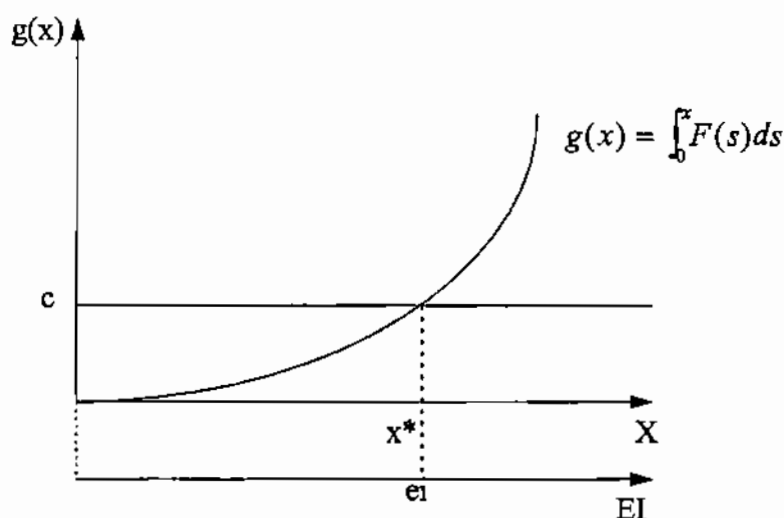


Figure 7.1

From this picture it can be seen that, given the distribution of offers on the market, the expected gain from continued search is positively related to the level of the offer drawn. This implies that if a consumer has found an appliance that is associated with one of the highest

life-cycle costs that is represented on the market, the gain from continued search is relatively high. It is furthermore clear that different search costs are resulting in different levels of reservation price for the consumers, i.e. a lower search cost c is associated with a lower reservation price x^* , given the distribution of offers.

In the figure there is a second horizontal axis drawn, representing the level of energy intensity EI associated with the different offers on the market. As can be seen the level of energy intensity for the average appliances purchased is then related to the level of search cost in the same way as the reservation price is. This implies that for a lower search cost the average consumer will search for an offer with a lower present value of life-cycle cost, and thereby end up purchasing a model that is less energy intensive.

The reservation level x^* represents the level for the average consumer, and it is of course possible that a consumer may draw an offer x that is much lower than x^* , in which case the consumer will purchase that appliance. This has the result that some consumers will end up buying appliances that are less energy intensive than the ones associated with the reservation price x^* , but in order to ensure that the average level of energy intensity is lowered, i.e. a lower x^* , the search cost c has to be brought to a lower level than initially.

Given the search cost c consumers will reject all offers above x^* , but they may end up purchasing appliances with an offer x lower than x^* . It is however not likely that all consumers can be assumed to belong to one homogenous group in which every one has the same search cost c . If consumers belong to different groups with separate search costs, it can be understood from the figure that this will result in different reservation prices for the groups, i.e. x^* will vary across consumers and thereby allowing a variety of models providing similar levels of service, but at different costs, to be sold.

7.3 A numerical example

In order to shed some more light on what the model implies it is useful to construct a numerical example. To do this we need to make several assumptions about the world in which the consumers are acting: How are the different energy using devices with their corresponding life-cycle costs distributed on the market? What are the lowest and highest price plus life-cycle cost for equipment that produce the same service? What is the search cost for a representative consumer? Assumptions about these factors have to be made in order to carry out a calculation of a consumer's reservation price. For the distribution of the products on the

market a reasonable assumption appears to be that they are uniformly distributed, i.e. the probability of finding a certain model is the same for all models present on the market.

The next assumption that has to be made concerns the spread of the offers that exist on the market. What is the cost of the best and the worst piece of equipment that can be obtained on one particular market? Johansson et al. (1989) show that for combined refrigerator-freezers with a volume of 500 liters, the best available model in Denmark in 1988 had an energy intensity of 550 kWh/year. With a price of electricity at 0,50 DKK/kWh⁴⁹ this implies a yearly cost of 275 DKK. If an expected life of 15 years for the appliance is assumed, and a discount rate of 4% is used, total expected energy cost can be estimated to 3,060 DKK. With a purchase price of 7,500 DKK this implies a total cost of 10,560 DKK over the appliance's life-cycle.

At the other end is the worst alternative that will end up costing the consumer 12,340 DKK over the years of ownership, following the same calculations and assuming an energy intensity of 1050 kWh/year and a purchase price of 6,500 DKK. These are the two extremes, and the market then consists of a full range of models representing life-cycle costs in between the two end-points. A crucial assumption is of course that the only thing that is different between the offers is the life-cycle cost, i.e. all the models supply the same level of service but at different costs. These life-cycle costs also reflect that the more cost-effective model is the more energy-efficient choice. This implies that cost-effective choices to reduce energy use can be made.

The third issue is the search cost, without which a well informed and rational consumer most likely would choose the least cost alternative without hesitation. In order to collect and use the needed information in appropriate calculations the consumer has to conduct a search. This cannot be carried out unless the consumer allocates some of his/her leisure time to the task, implying that the main part of the search cost is the amount of time the consumer has to spend on the process. As discussed earlier, time is a scarce resource for the household and the individual consumer, and the foregone leisure time should therefore be valued at the opportunity cost of not using it for some other task. The individual consumer's opportunity cost of one hour of leisure is, at the margin, equal to the amount of net income that an extra hour of work would have given. Since it is an extra hour of leisure time that has to be spent in the search process it is reasonable to assume that the consumer's marginal cost of an hour spent on search is equal to the net income of an hour of work. In the case of Denmark a fair

⁴⁹ 1 DKK = 0.15 US \$, October 3, 1997.

estimate of this amount is 70 DKK/hour. How many hours is spent on search by the average consumer? The number of interest is the one that reflects the time spent on each search when information of one model is collected and used in calculations. For the purposes here it is assumed that the average consumer has to spend four hours of leisure time in order to thoroughly examine an offer found on the market. In a survey by Björkqvist and Wene (1993) it was found that on average a consumer spends approximately 12 hours from the start of the search to the point in time when the final decision is made about a purchase of equipment. This implies in our case that the average consumer examines around three different offers before making a purchase decision.

With the data above used to compute a reservation price that makes the equality $g(x^*)=c$ hold, it is found that given a search cost of 280 DKK the reservation price for an offer is 11,560 DKK for the average consumer. In other words; the consumer will continue to search for a better offer until one for less than, or equal to, 11,560 DKK is found, then the search is terminated since the expected gain of continued search is less than the cost of more search. This reservation price is clearly above the best offer that is available on the market, but given the search cost facing the consumer when collecting and using information, it is rational to behave accordingly and not continue the search until the offer with the lowest cost is found with certainty.

How does this relate to the average appliance actually purchased? According to Johansson et al. (1989) the average combined refrigerator-freezer (500 liters volume) purchased in 1988 had an energy intensity of 800 kWh/year. This generates an estimated life-cycle cost for energy equal to 4,450 DKK, following the same assumptions as used above. This energy cost added to a purchase price of 7,000 DKK gives a total life-cycle cost of 11,450 DKK. This figure is less than, but close to, the reservation price generated from the search cost model above. From this the conclusion can be drawn that consumers are not necessarily acting irrationally when they pass up opportunities to purchase the most energy-efficient models on the market. Instead the observed behavior could be interpreted as rational behavior from consumers facing a search cost of 280 DKK when making their purchase decisions. The observation that the life-cycle cost of the average appliance sold is lower than the computed reservation price suggests that some consumers do find an offer below their reservation price level and purchase it accordingly.

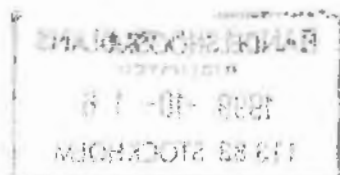
Another interesting aspect of the discussions above is to calculate something that could be labeled as the sensitivity of the reservation price to changes in the search cost, i.e. how much the reservation price changes when the search cost changes. If the search cost decreases by

10% from its original level of 280 DKK the resulting decrease in the average consumers reservation price is less than 1.00%. This implies that substantial decreases in the search cost have to be realized before the reservation price will be close to the life-cycle cost of the most cost-effective model on the market. This fact is emphasized further by the finding that at a required search time of only one hour/search, or a search cost of 70 DKK, the reservation price is computed to 11,060 DKK. If the search instead is costless, i.e. no time has to be spent to find the appropriate information, the reservation price for an offer is equal to 10,560 DKK or the best possible offer, as would be expected.

The numerical example used here is calculated to show the results on average for a representative consumer. Before leaving this section I would like to point out that it is not self-evident how to carry out the calculations for potentially cost-effective aggregate energy savings since there is a great amount of heterogeneity in the population, i.e. what is a cost-effective energy saving for one group of consumers must not necessarily be the best alternative for every consumer.

7.4 Concluding remarks

This chapter has shown that the existence of a search cost may partially explain the apparent anomaly between existing opportunities to cost-effectively conserve energy and the finding that these possibilities are yet not fully exploited. The observed behavior may not indicate irrational behavior on behalf of the consumers, but rather that they include a cost for the search when making purchase decisions. In the numerical example it was shown that the search cost almost has to be eliminated in order to ensure that the consumers search for the most cost-efficient, and thereby most energy-efficient, model on the market. This implies that, if reduction of search cost is to be an important policy instrument to reduce energy use cost-effectively, it is vital that the measure taken (e.g. pooling of information) is an inexpensive method to effectively reduce the individual consumer's search cost.



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